New Opportunities in Neutrino Physics
BNL Accelerator Forum

Milind Diwan 12/16/2004
Brookhaven National Laboratory
Upton NY 11776

- Brief Review
- Description of Oscillations
- Recent Progress and Implications
- What to expect in 5 years
- Ambitions for DUSEL!

Thanks to many for slides.
esp: SK, SNO, Kamland, Minos

BROOKHAVEN
NATIONAL LABORATORY

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

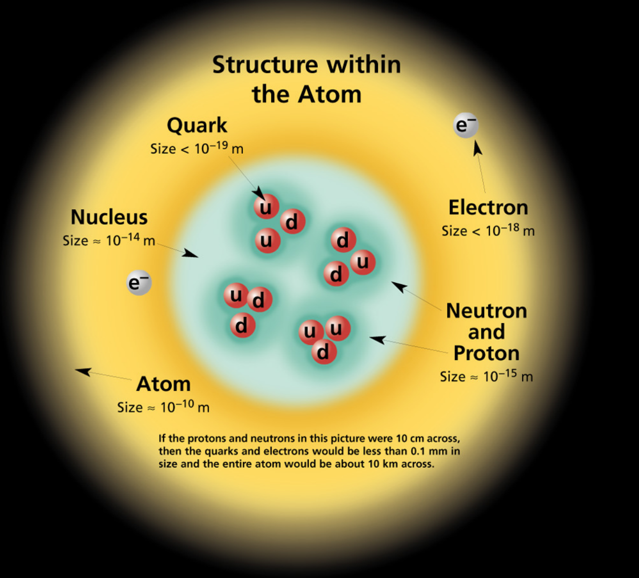
Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

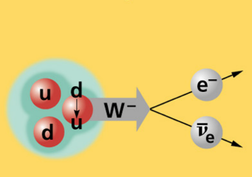
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

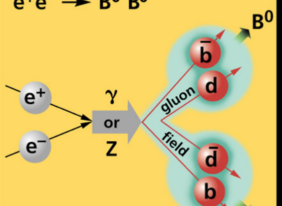
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



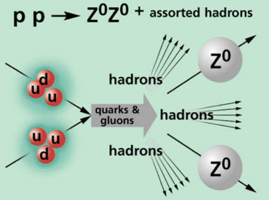
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\,\bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

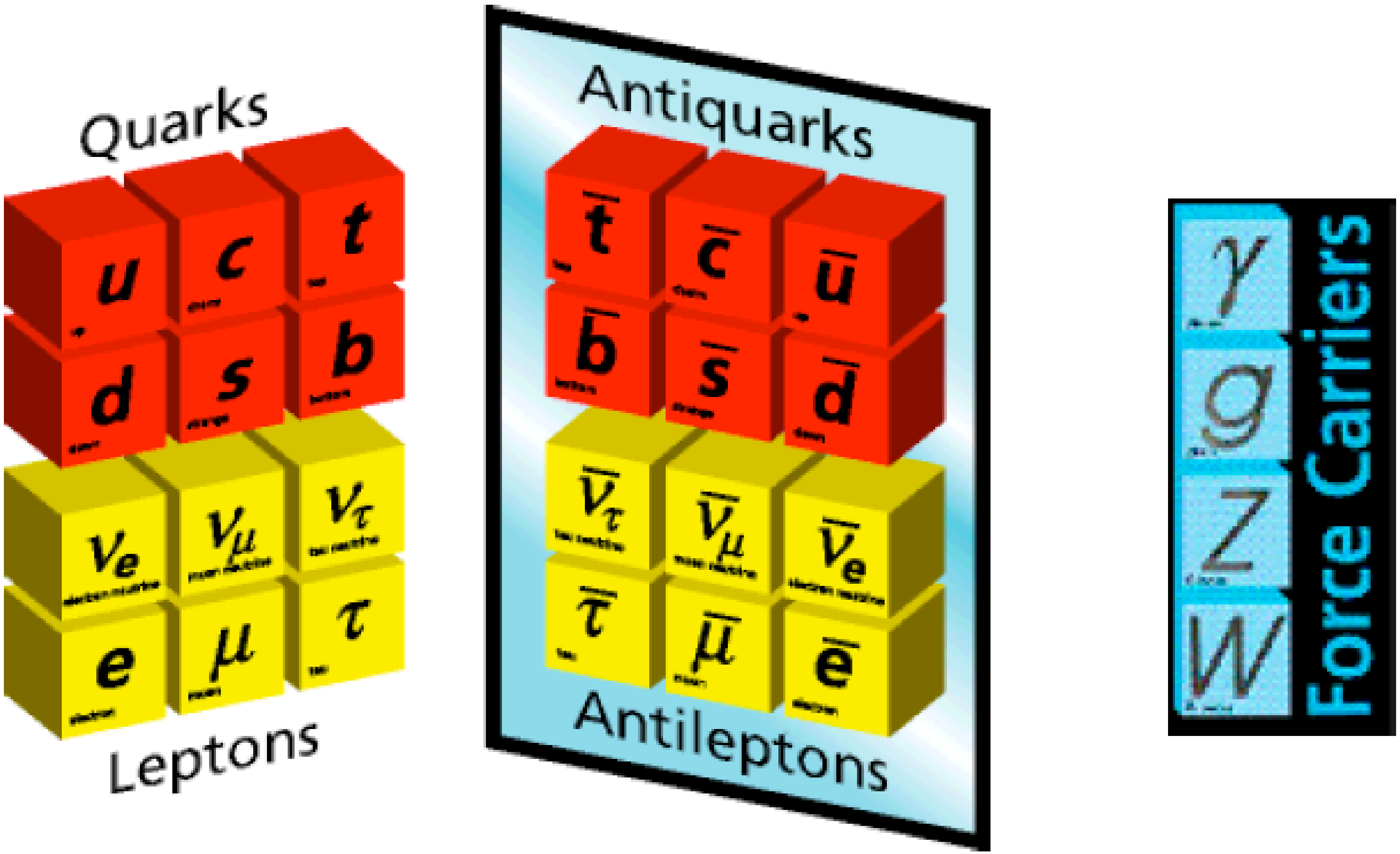
The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

The Standard Model

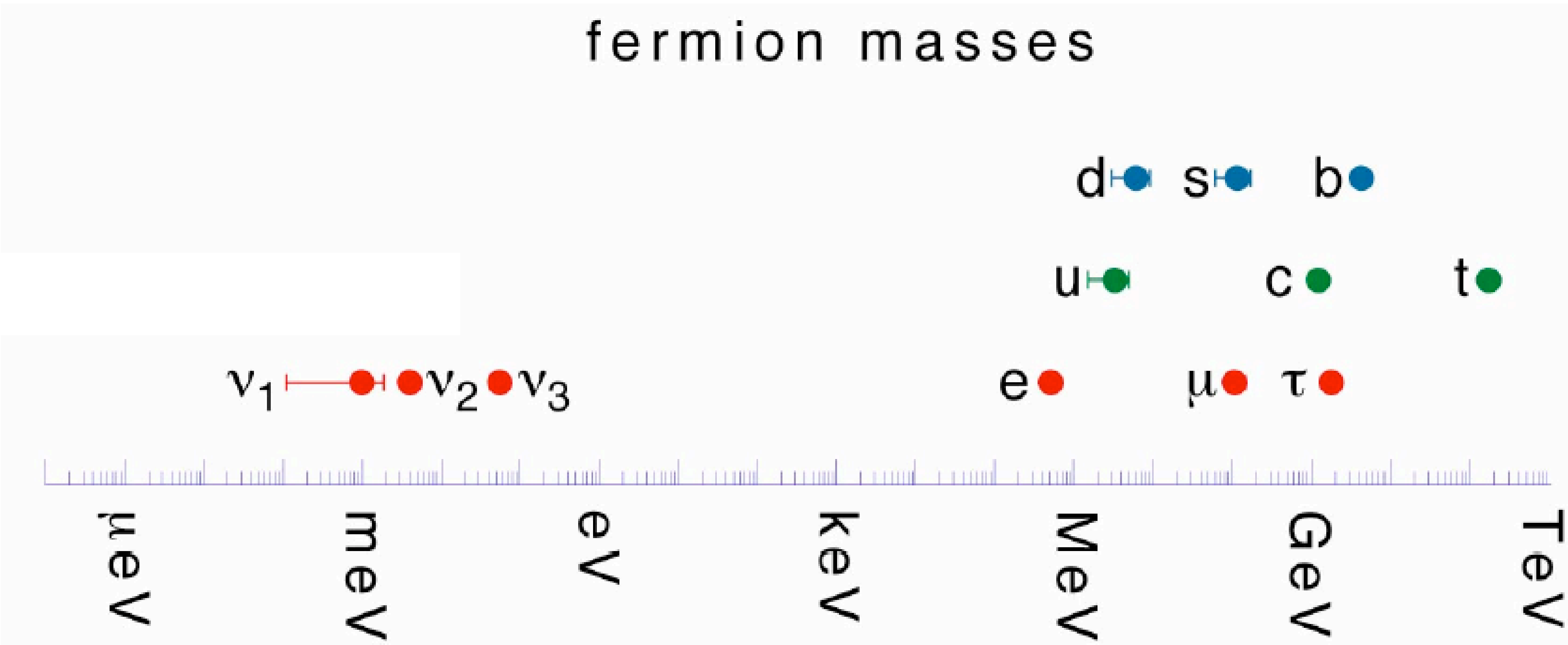


This picture needs revision

Neutrino puzzles

- Do they have mass ? Why so small ?
- If they have mass what implications on left-right properties ? Why are neutrinos only left-handed ?
- Can they turn into each other ? Break the conservation separate lepton number?
- What implications for the structure of the universe ?
- What is the relationship to quarks ?

Current picture of masses from oscillations puzzling.



hierarchy

ν_1 fixed at 1 meV in this picture

Why Mass could imply Lepton number violation

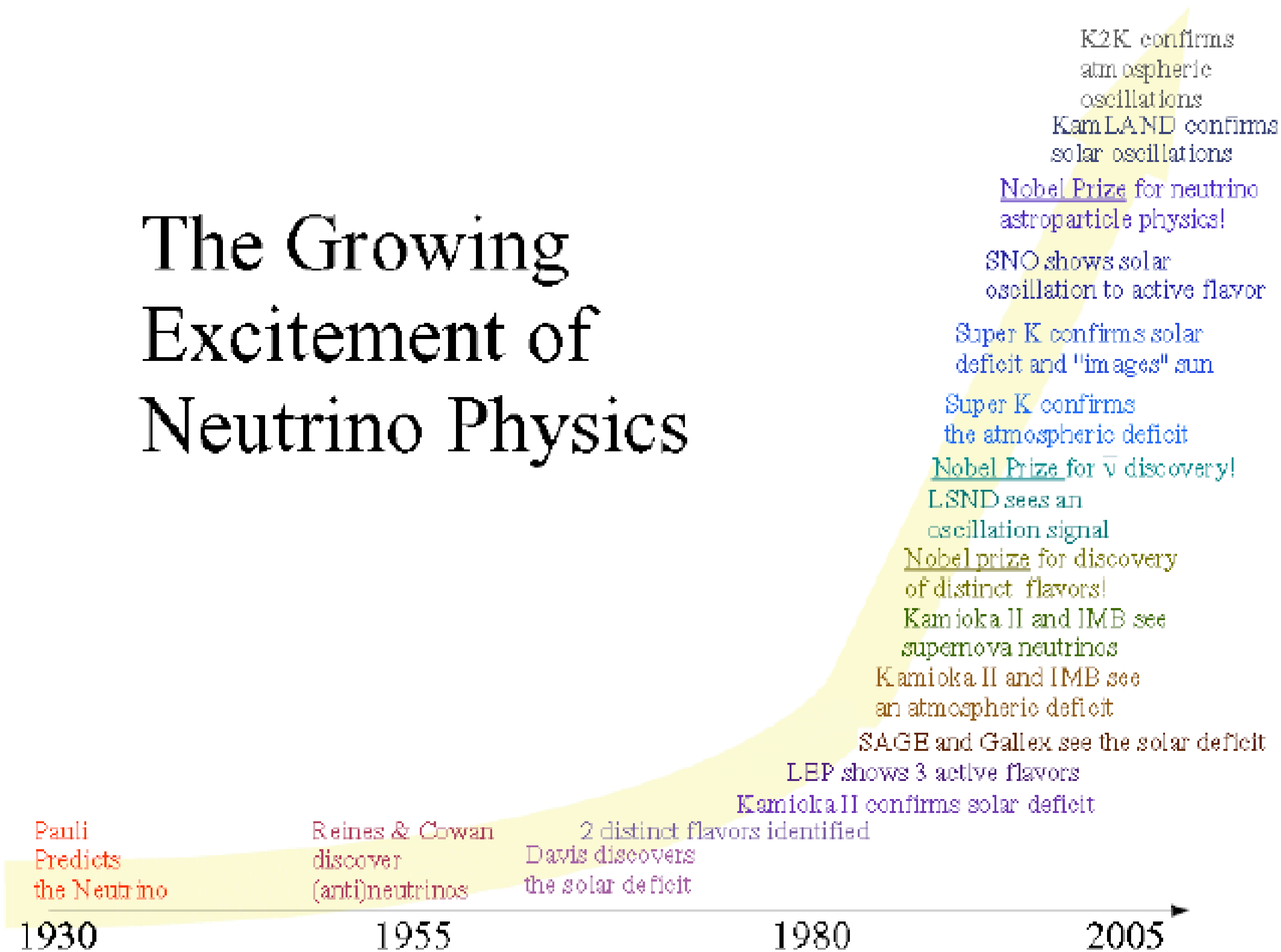
	Particle	Anti-particle
Left	$(e \quad \nu)_L$	$\overline{(e \quad \nu)_L}$
Right	$e_R \quad \nu_R$	$\bar{e}_R \quad \bar{\nu}_R$

- Standard model has only left handed leptons in isopin states. But if neutrino has mass it can become right handed.
- If $\bar{\nu}_L = \nu_R$ then neutrinos are their own antiparticles and can annihilate themselves.

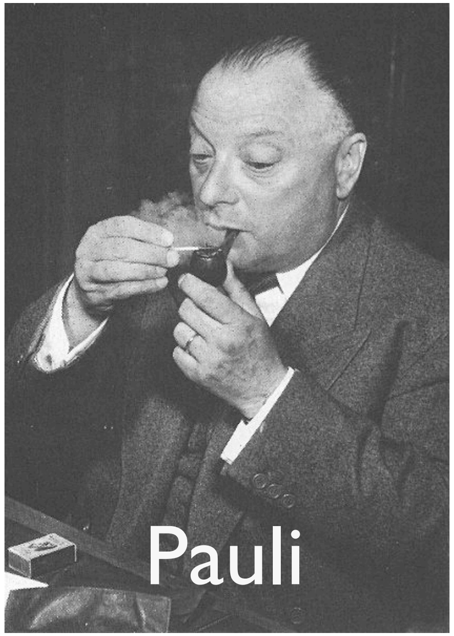
Importance of the Physics

- Neutrino mass and mixing has deep implications for conservation laws (especially lepton number)
- Also has deep implications for cosmology: contribution to dark matter and baryogenesis (leptogenesis).
- Mass and mixing are fundamental parameters. Their values contain hints about the underlying physics of matter.

The Growing Excitement of Neutrino Physics



From APS neutrino study

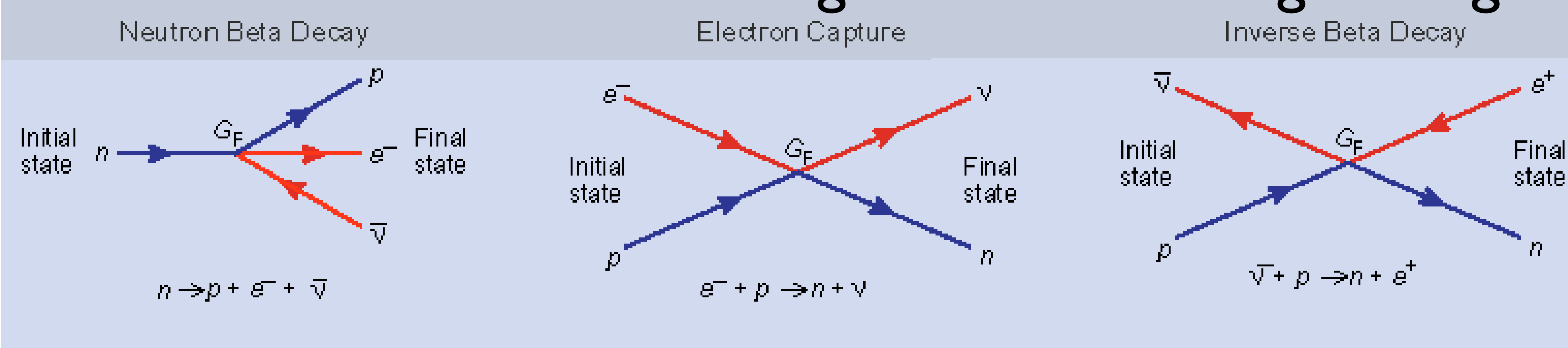


Inventor

Developer

Oscillator

Charged current: change charge



Neutral current: neutrino does not change charge

Brief review of oscillations

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

Appearance

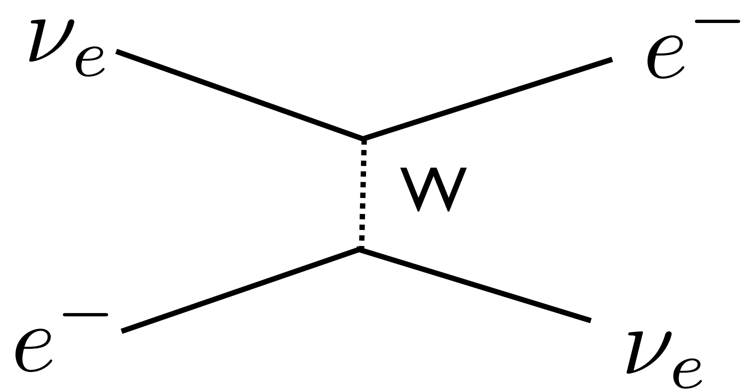
$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Disappearance

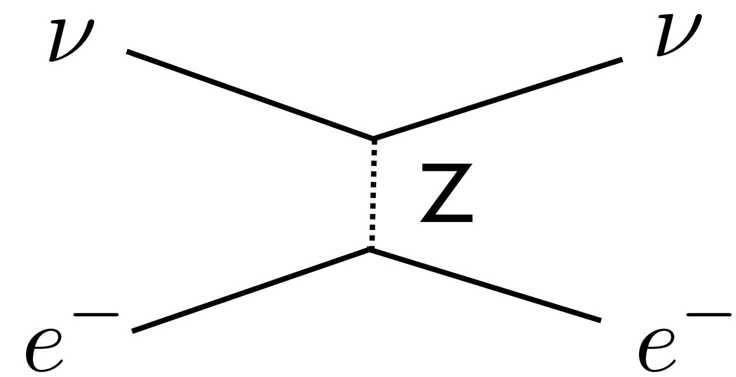
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ ($\pi/2$): $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

$$i\frac{d}{dx}\nu_f = HR_\theta \nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.



Charged Current
for electron type only



Neutral Current
for all neutrino types

Additional potential for ν_e $(\bar{\nu}_e)$: $\pm\sqrt{2}G_F N_e$

N_e is electron number density.

Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

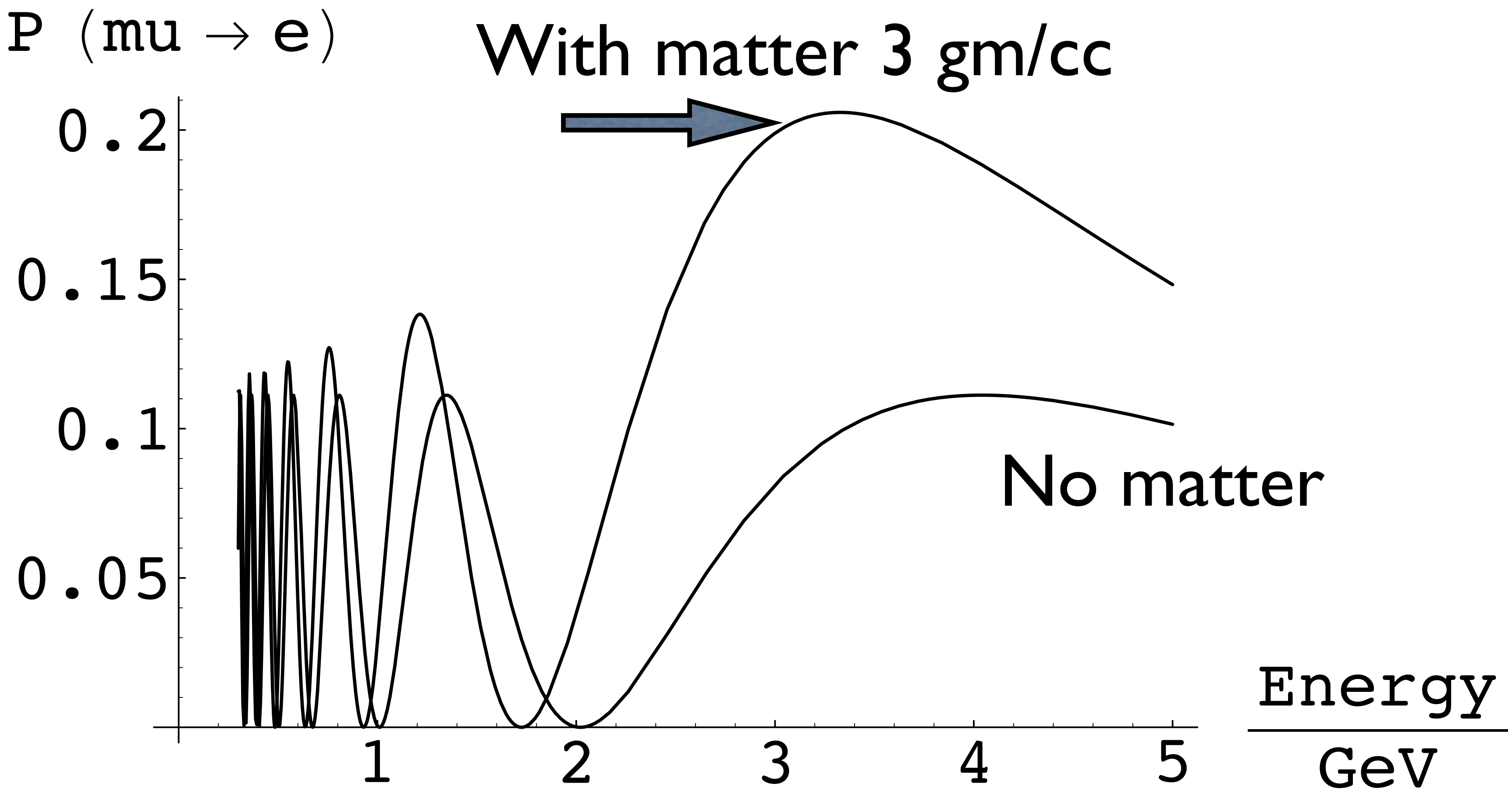
$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{4E}\left(R_\theta \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} R_\theta^T + 2E\begin{pmatrix} \sqrt{2}G_F N_e & 0 \\ 0 & -\sqrt{2}G_F N_e \end{pmatrix}\right)\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \tag{3}$$

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta} \times \sin^2 \frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2 + \sin^2 2\theta}$$

$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5} \times D/(gm/cc) \times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \tag{4}$$

Important only if electron neutrinos in the mix

2-neutrino picture



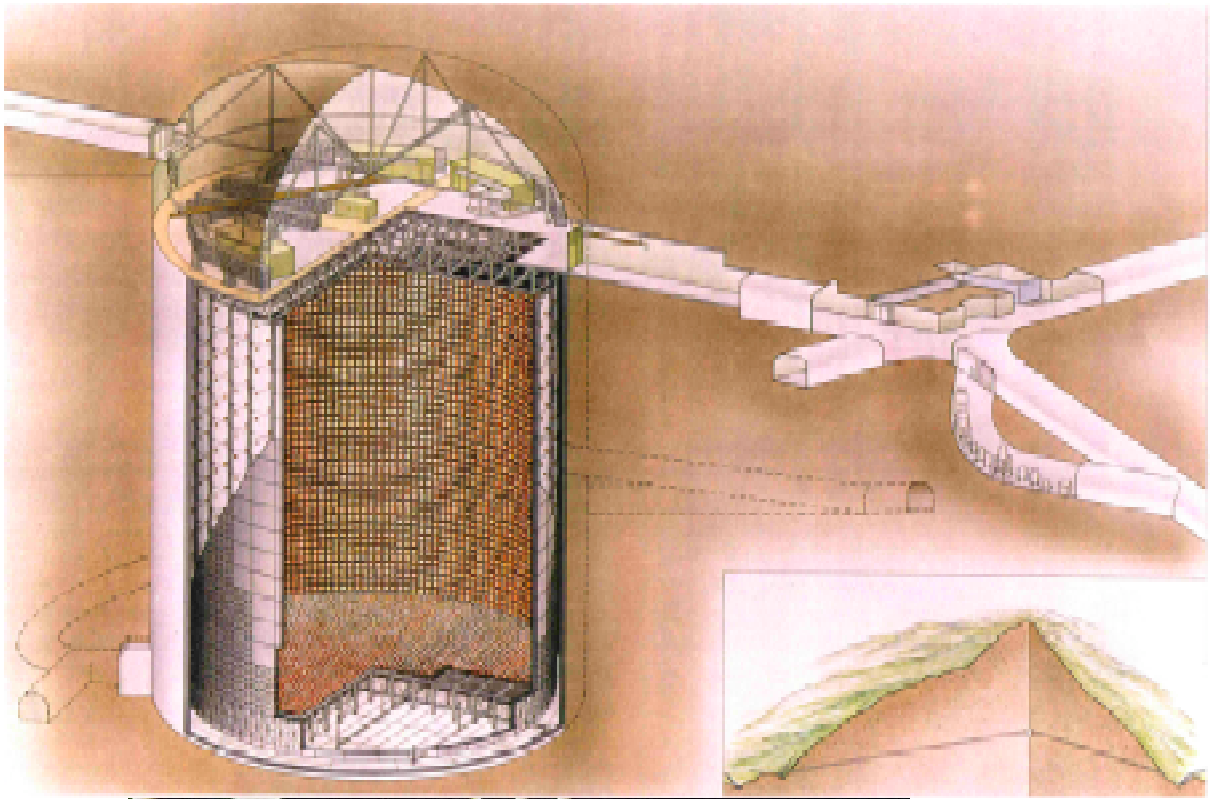
Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

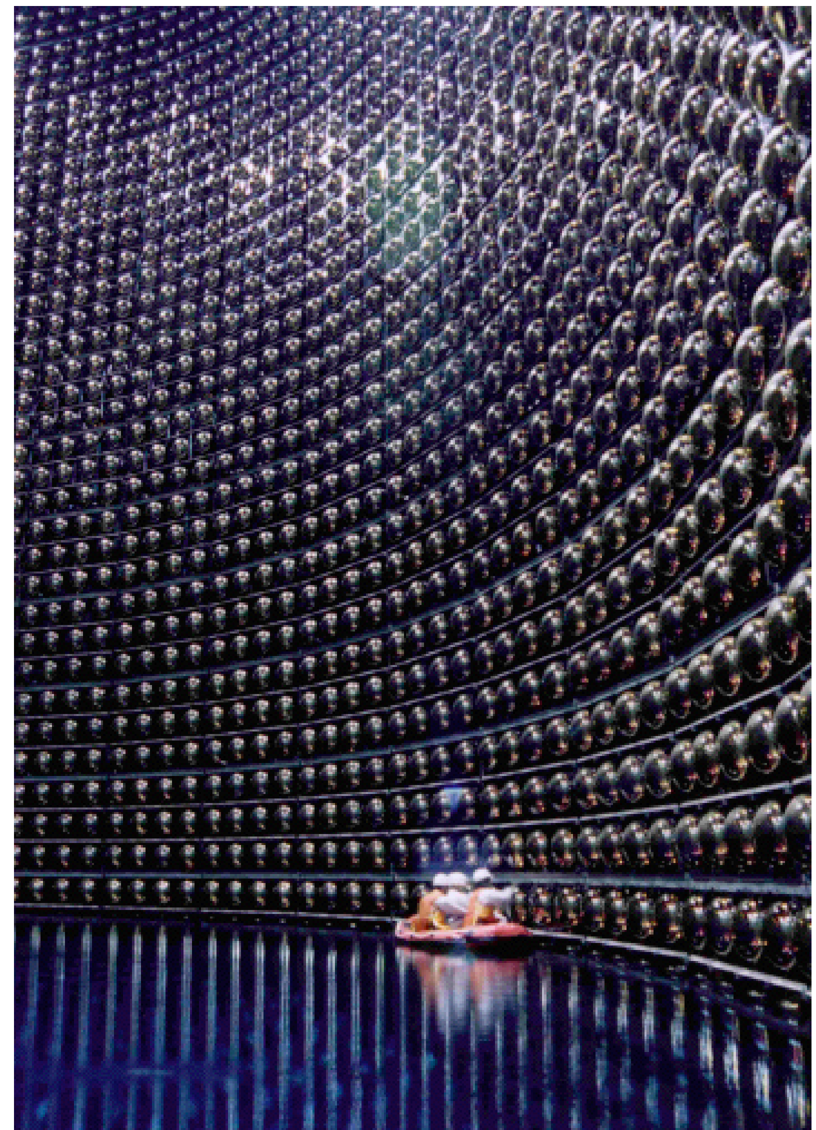
Key new evidence

- Super KamiokaNDE (SK): observe atmospheric neutrinos.
- Sudbury Neutrino Observatory (SNO): observed solar neutrinos.
- KEK to SK accelerator beam
- KAMLAND reactor experiment

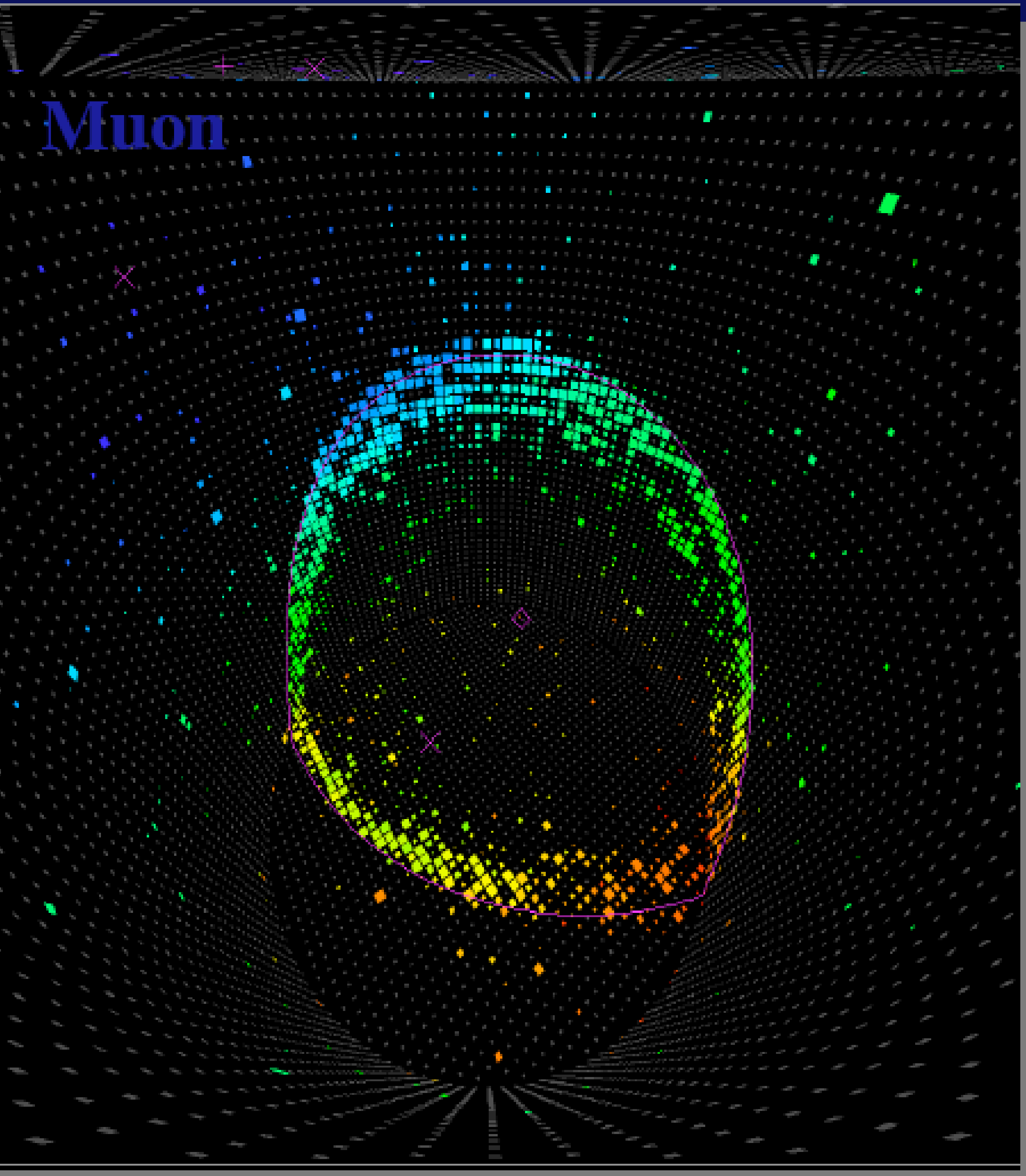
Apologies to many other pioneering experiments
Davis, Gallex, Sage, IMB, Kamioka, and reactor/accelerator

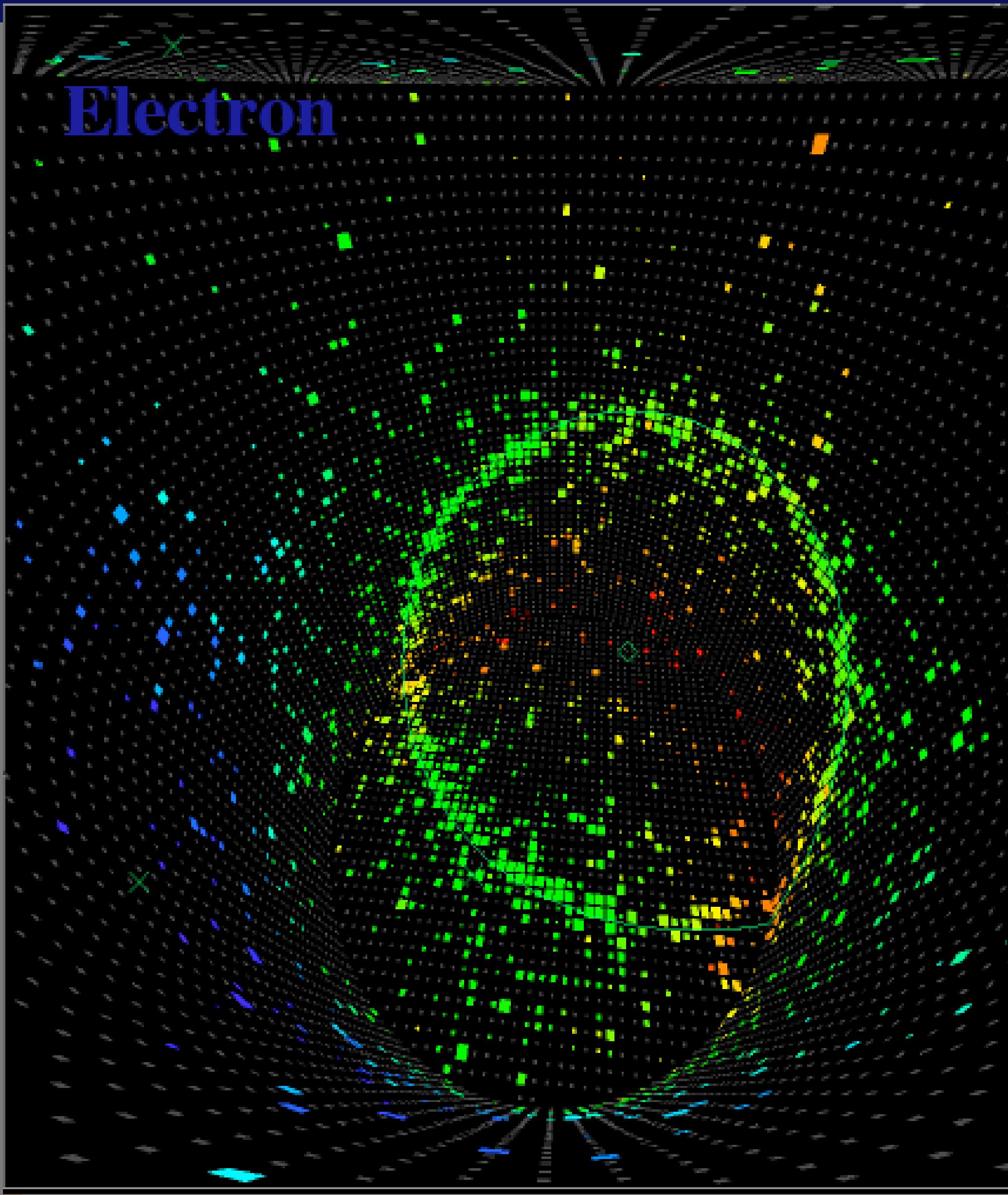
SuperKamiokaNDE



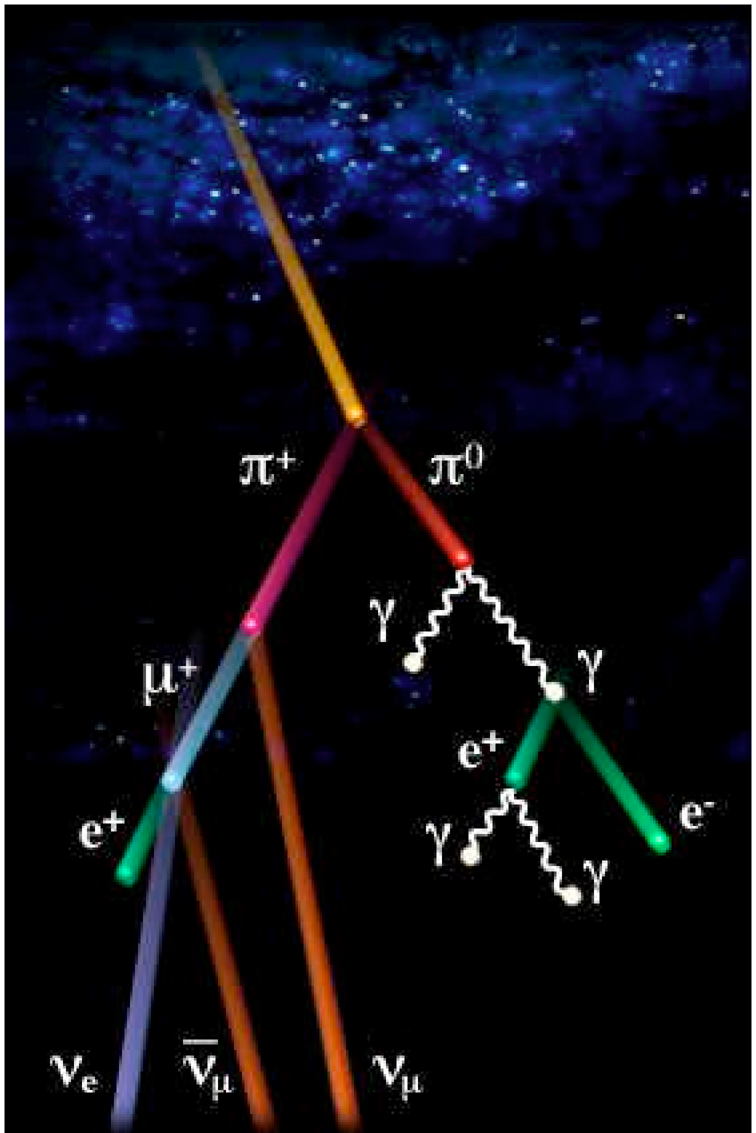


Particle Identification





Atmospheric Flux

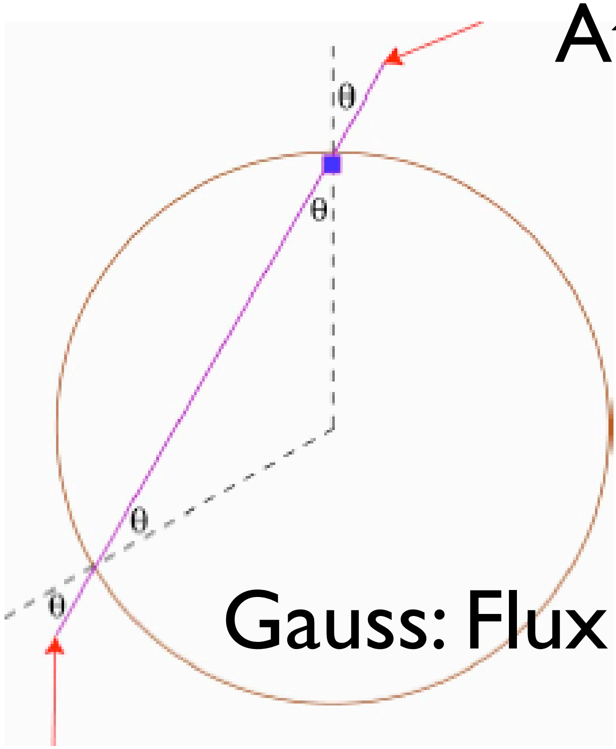


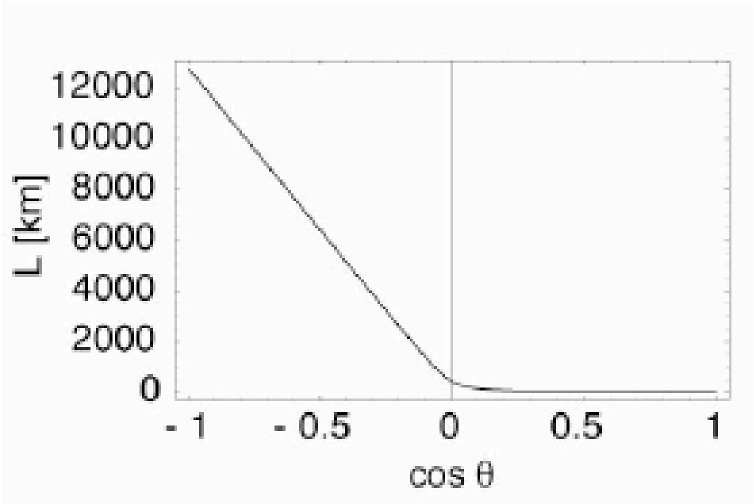
About 5000 neutrinos/m2/sec

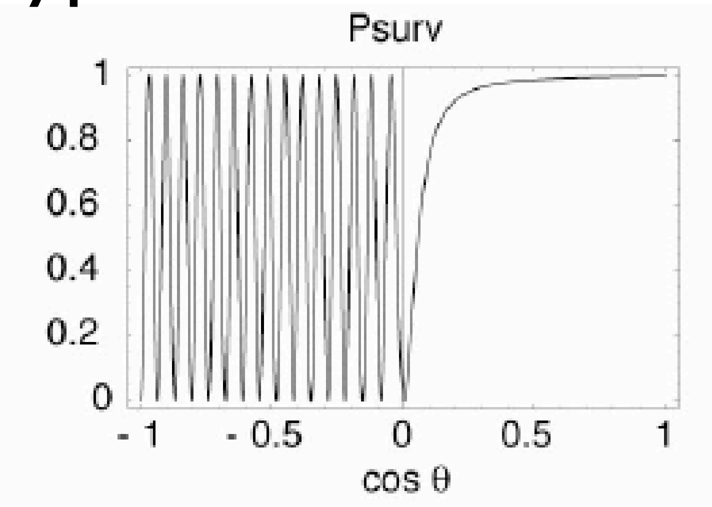
Event rate: (1/8) /Ton/yr
E>300MeV,
constant throughout earth

Atmospheric neutrinos as a source for oscillation experiments

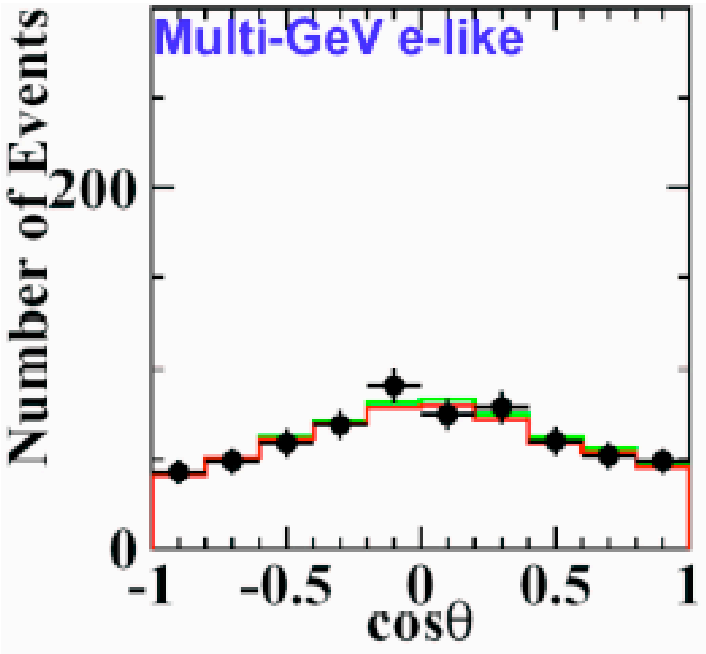
Atm. neutrinos 2:1 mu:e type

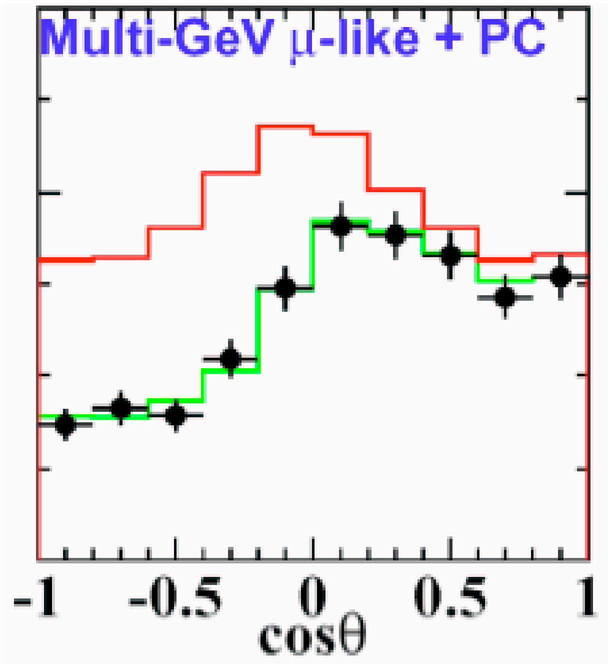






Gauss: Flux inside spherical shell isotropic

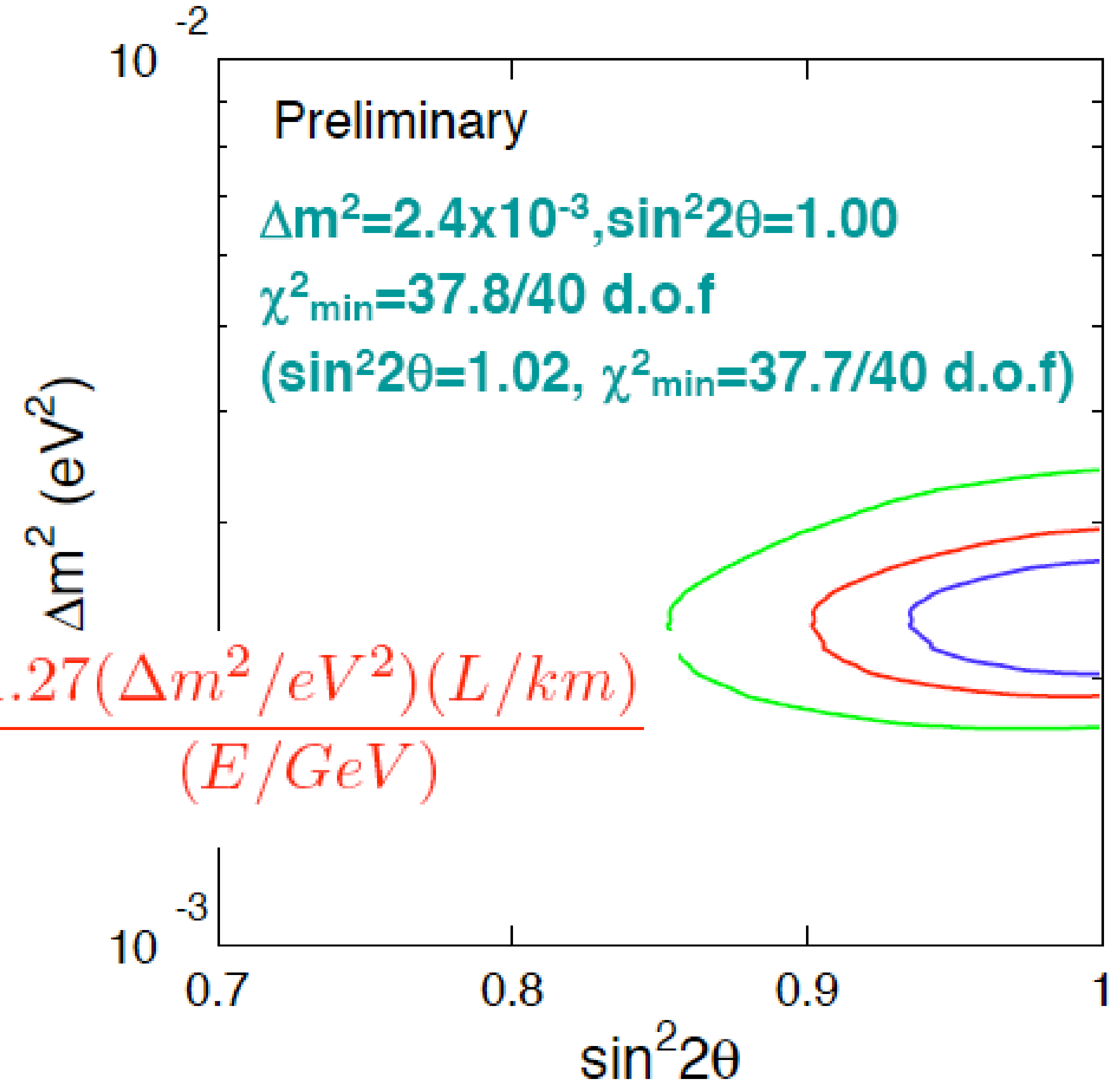




Evidence for neutrino oscillations from SuperK

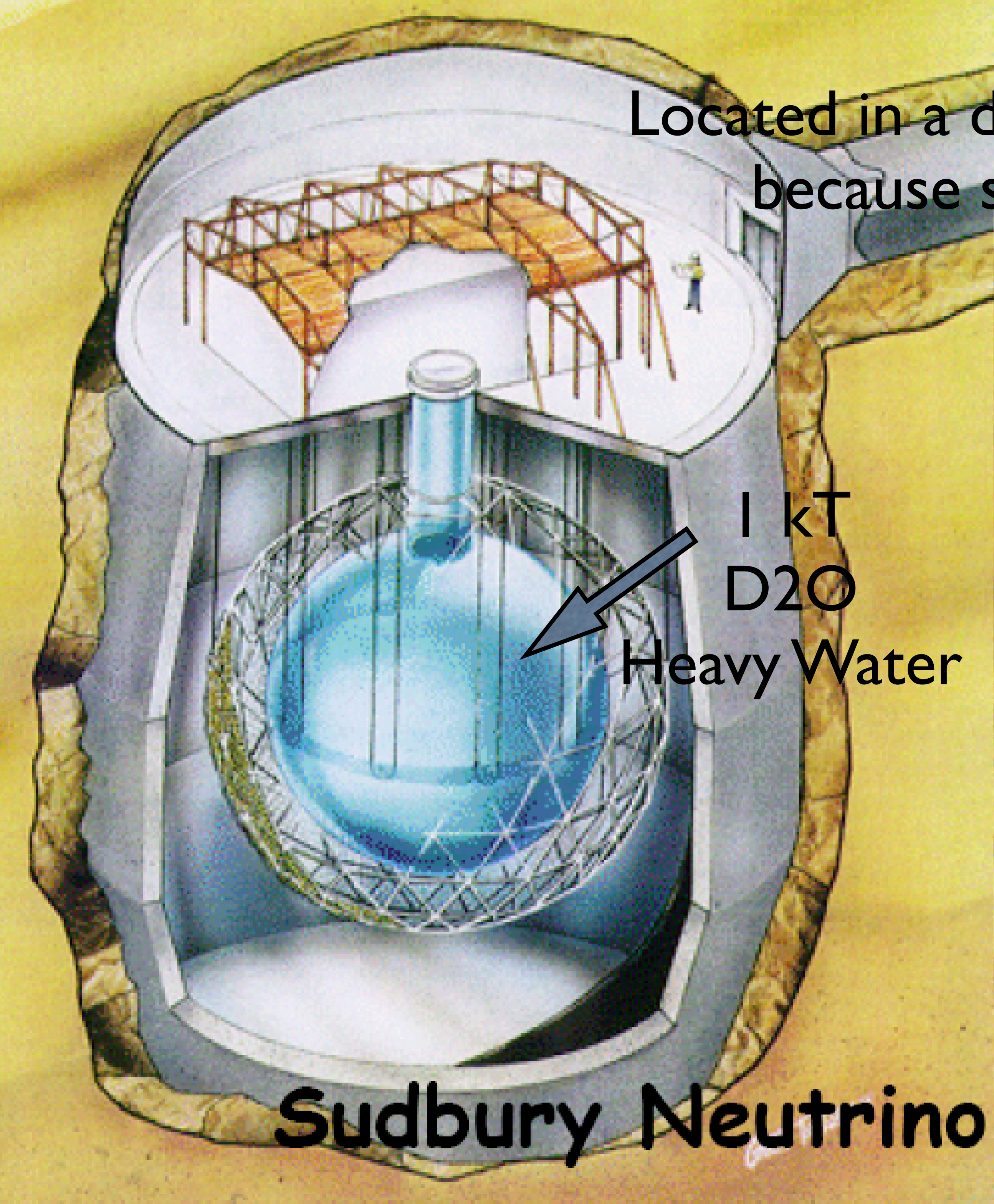
SuperK result

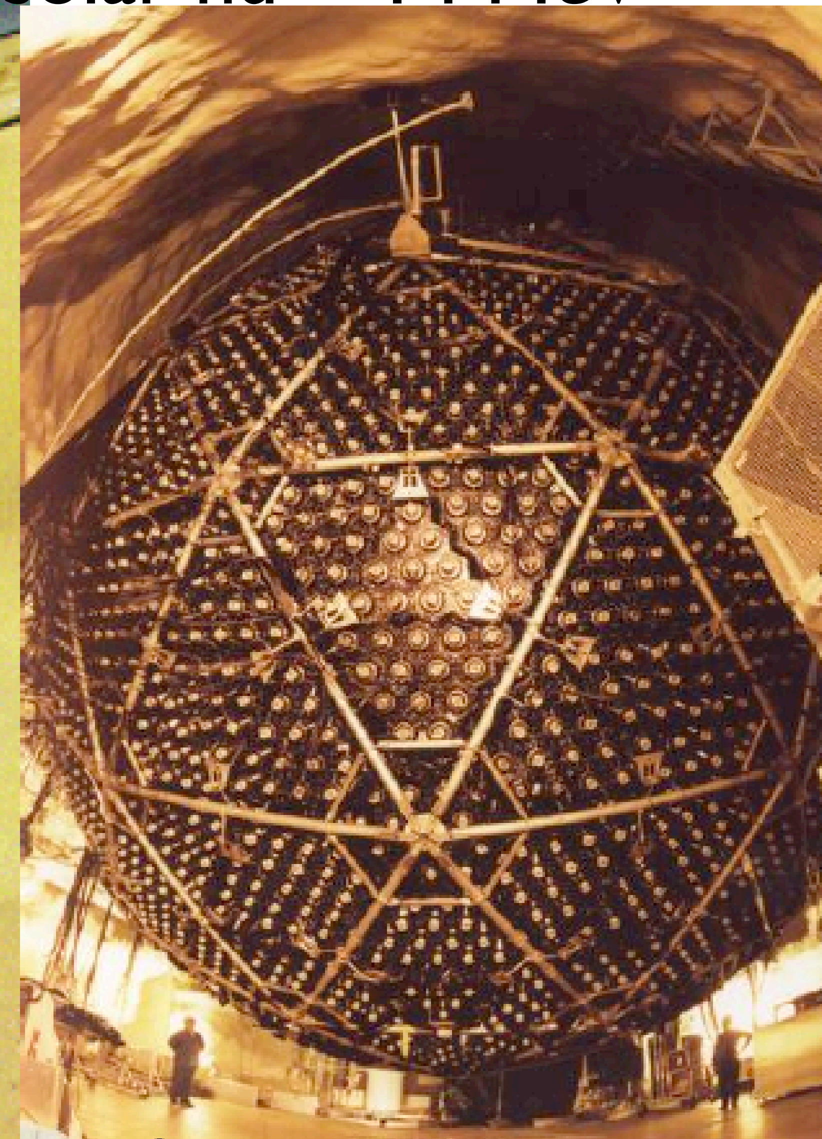
From fitting up/down distributions for disappearance



$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Located in a deep mine ~ 6000 mwe
because solar nu < 14 MeV





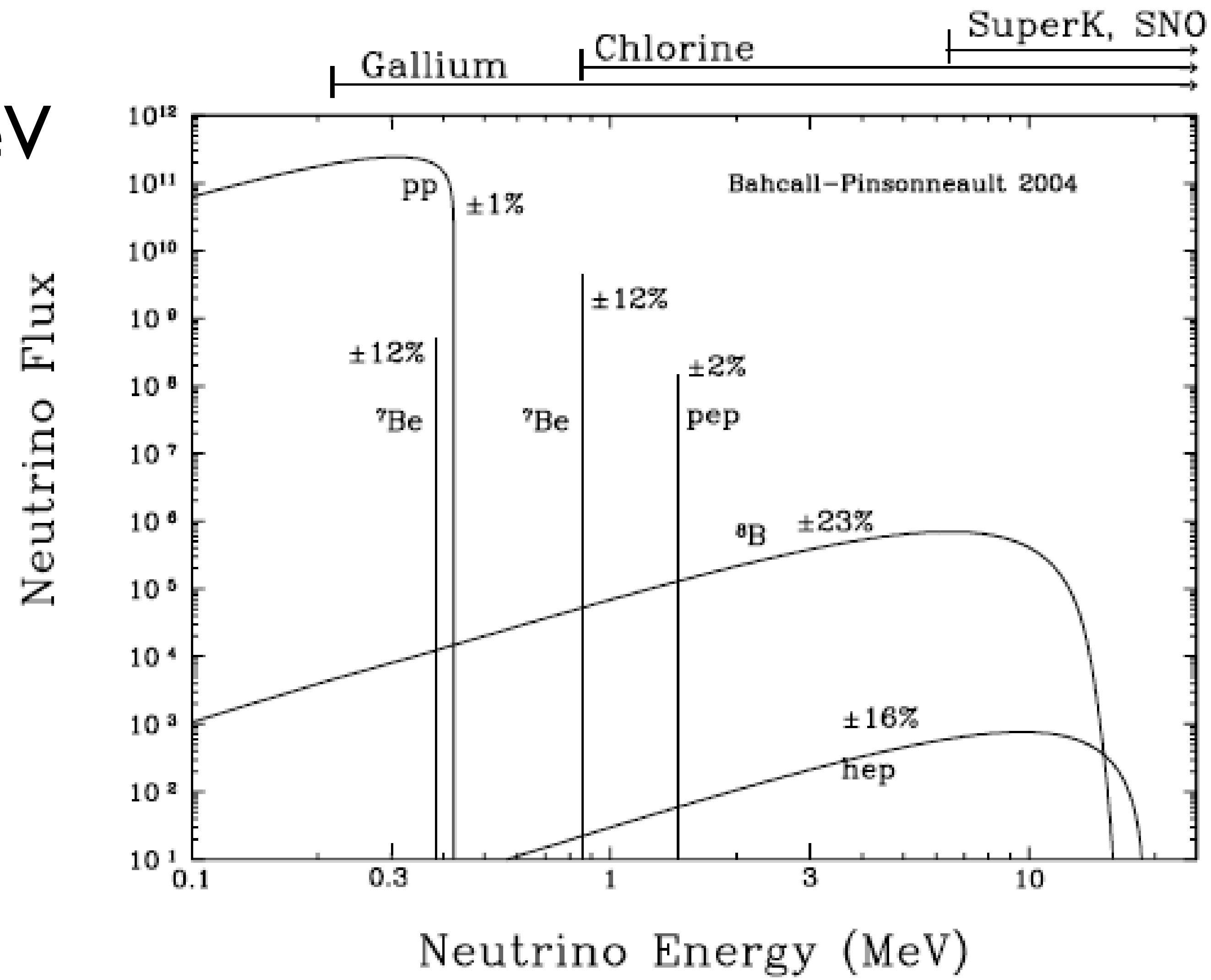
Sudbury Neutrino Observatory

The source for SNO

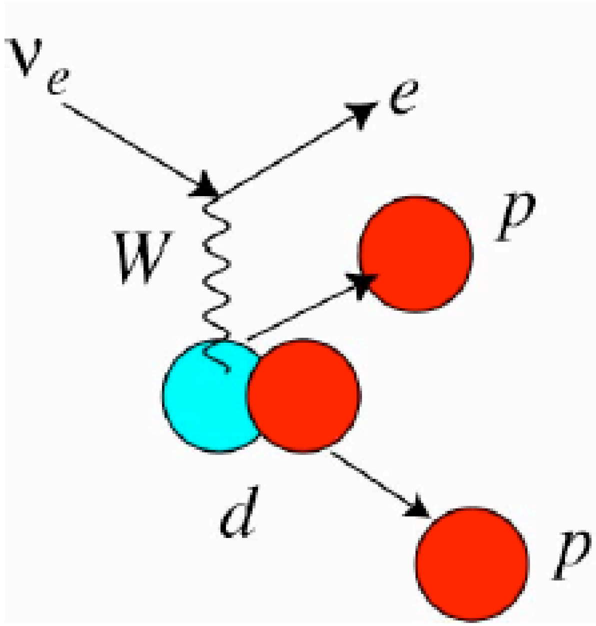
Flux in cm2/sec/MeV

For line sources
it is cm2/sec

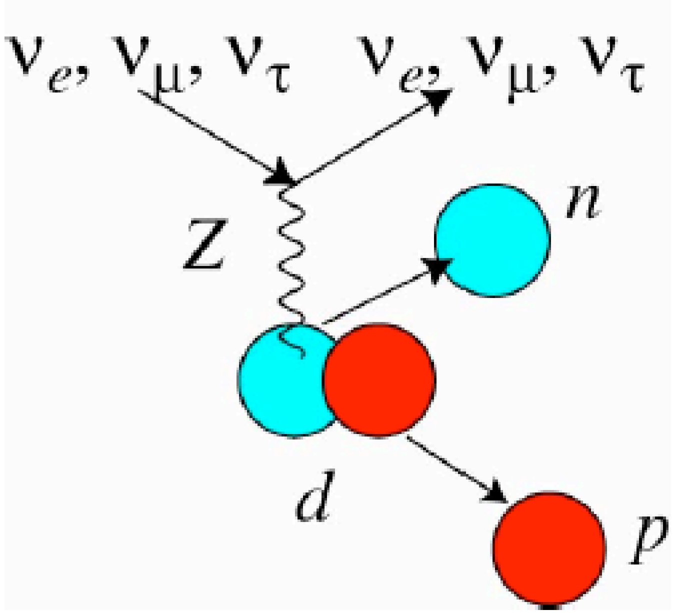
All
electron
neutrinos



Why does SNO use $300M worth of heavy water?



Charged Current

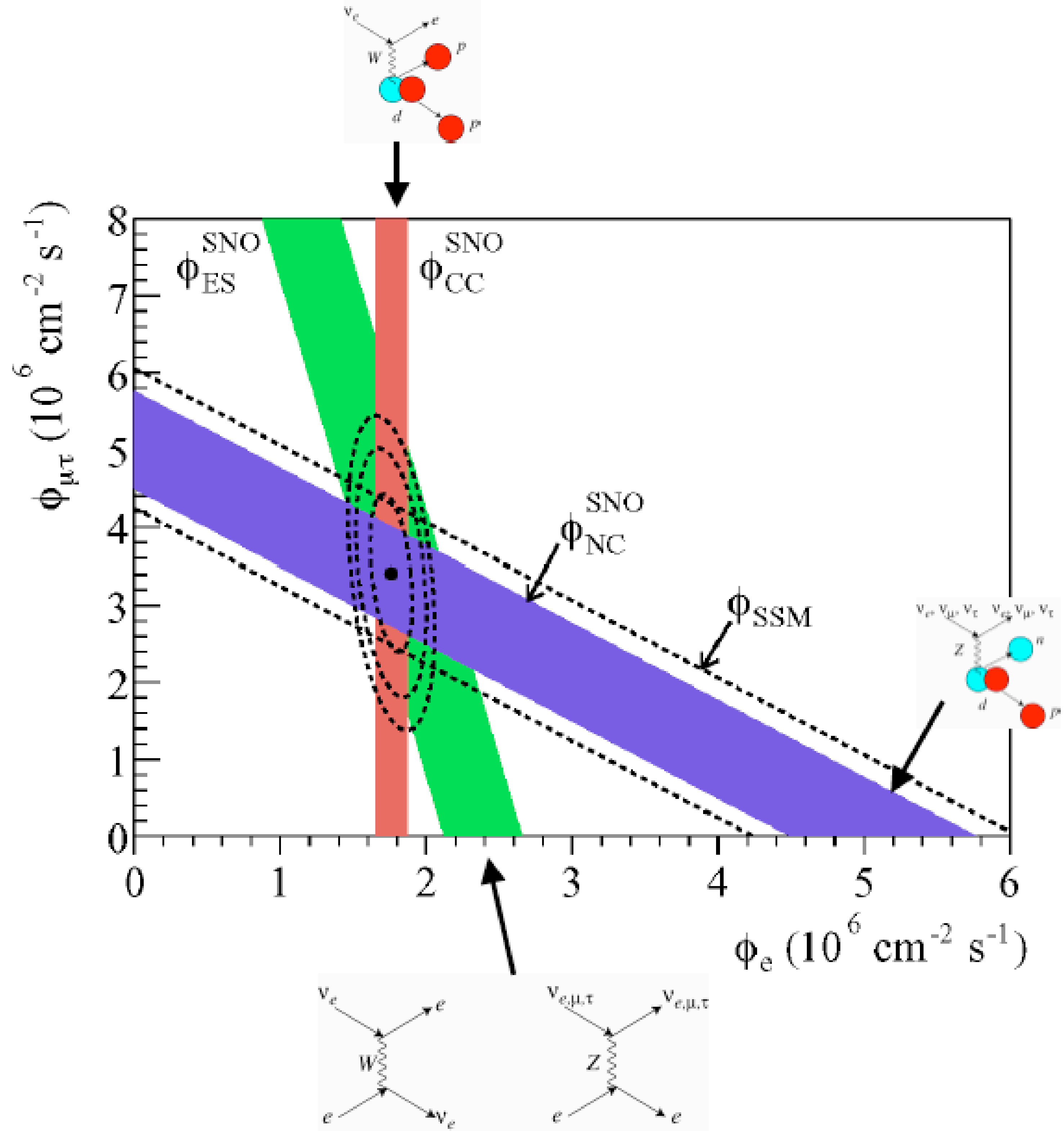


Neutral Current

Fluxes

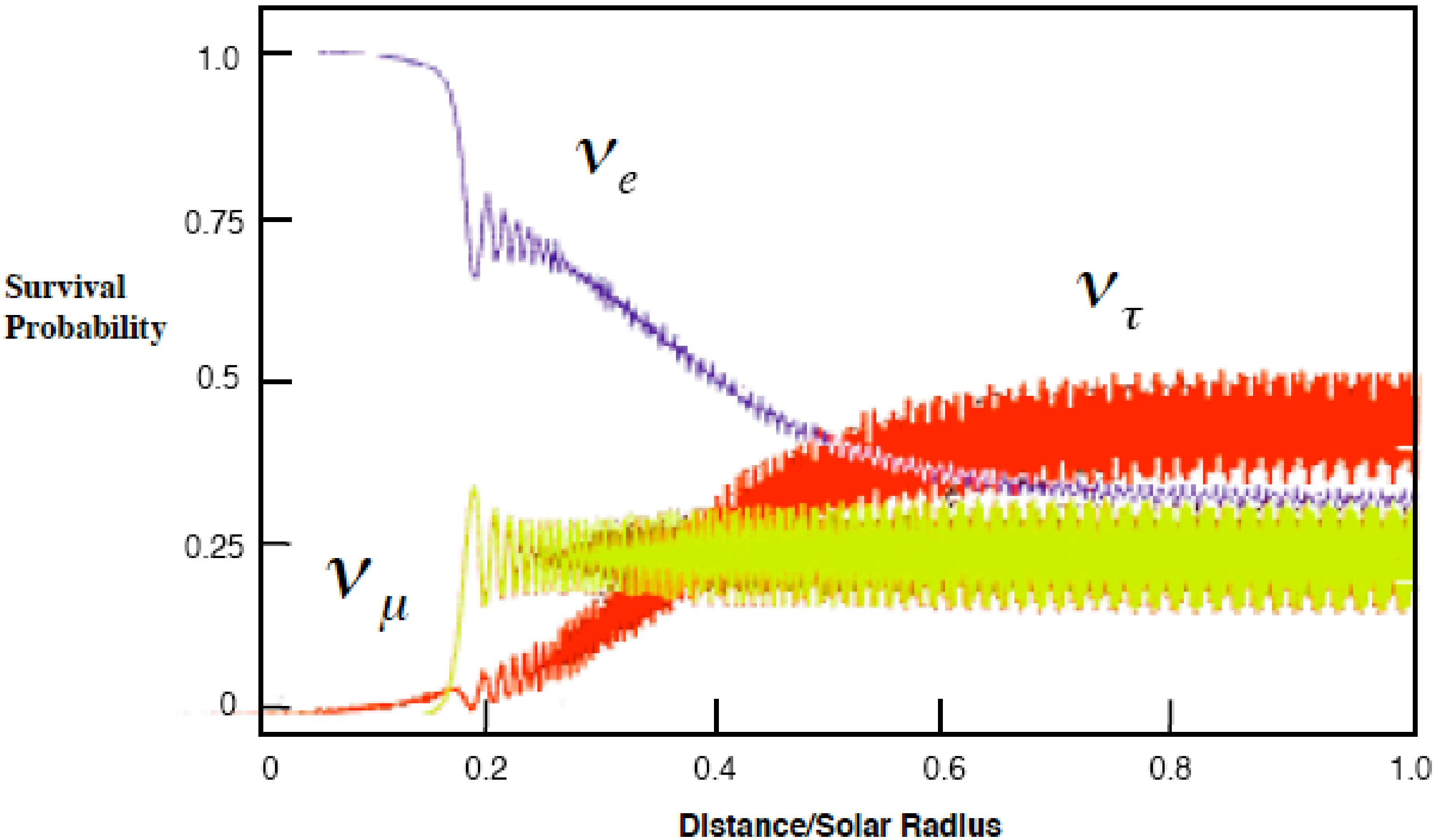
(10^6 cm^{-2} s^{-1})

ν_e:	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total}:	5.09(64)
ν_{SSM}:	5.05

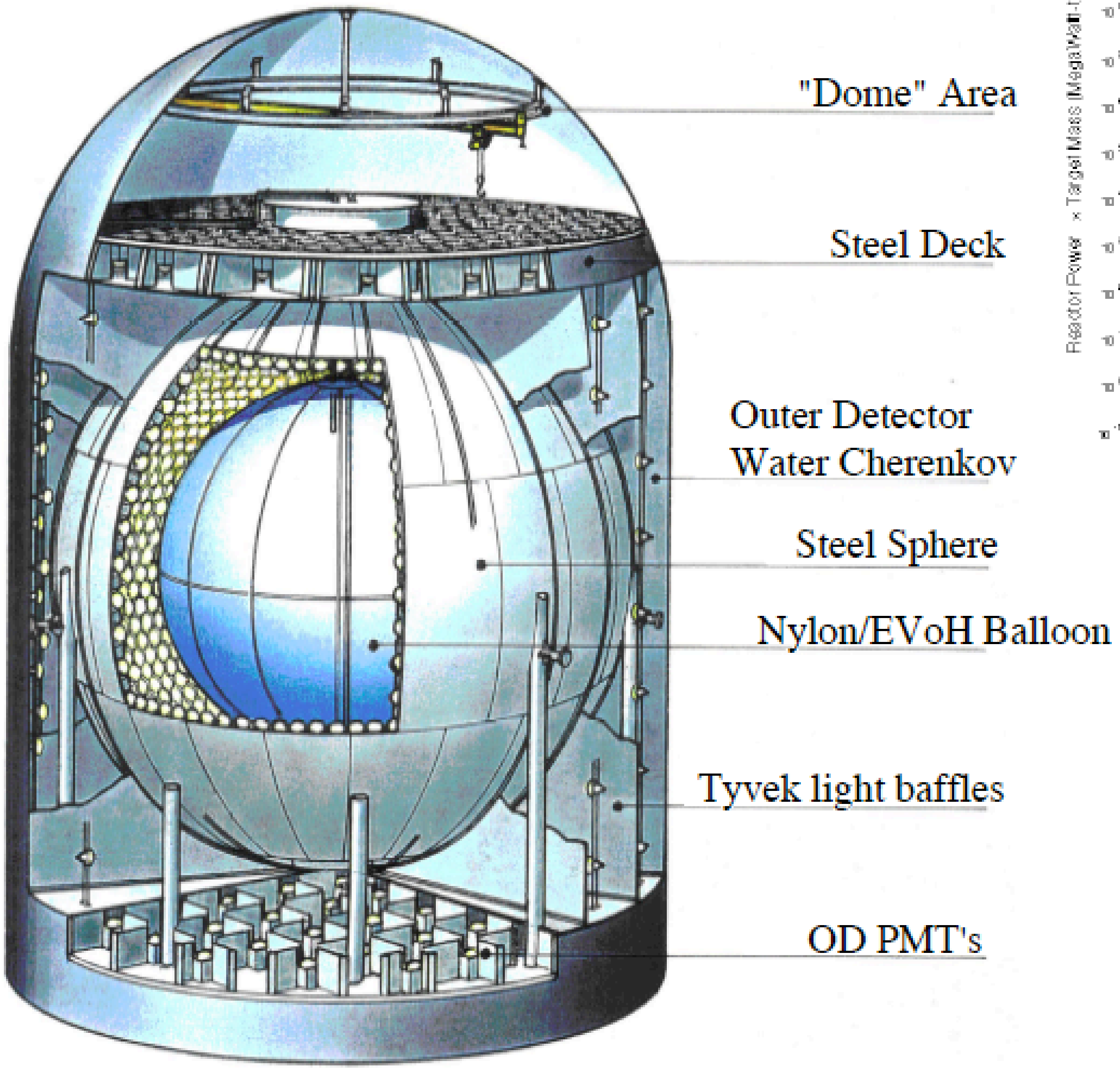


MSW Effect

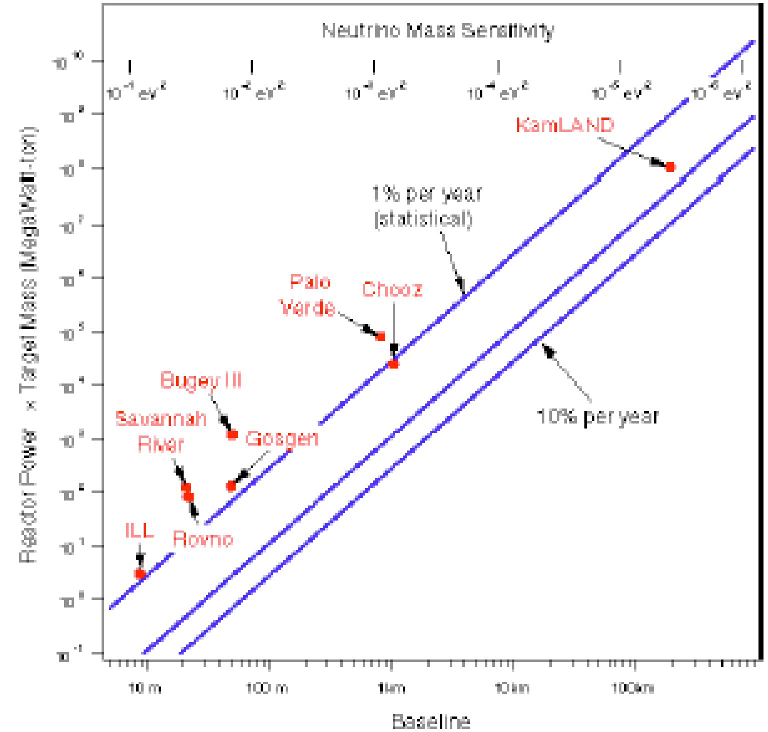
ν_e NC and CC ν_τ ν_μ NC only



KamLAND



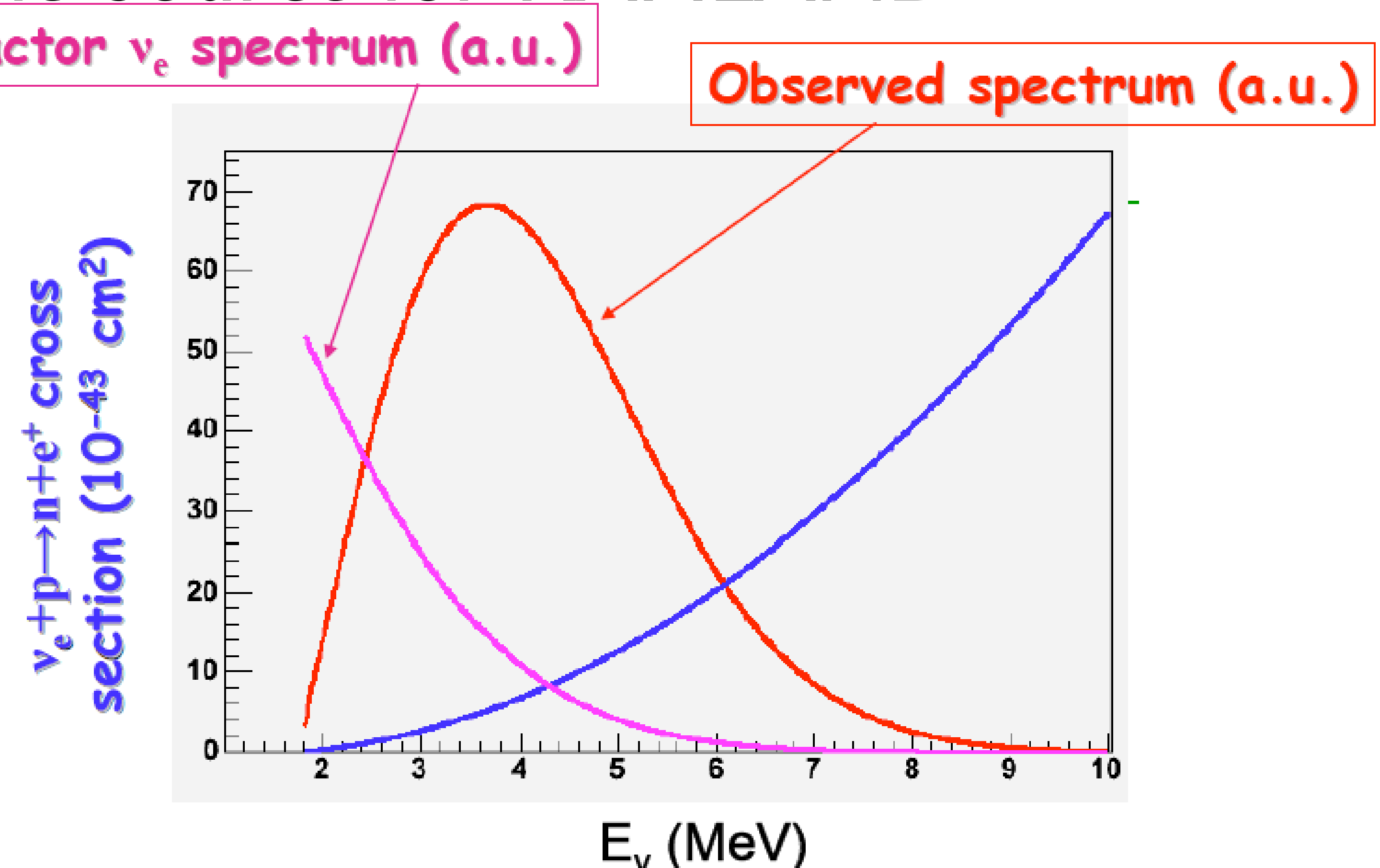
"Dome" Area
Steel Deck
Outer Detector
Water Cherenkov
Steel Sphere
Nylon/EVoH Balloon
Tyvek light baffles
OD PMT's



Neutrino Mass Sensitivity
KamLAND
1% per year
(statistical)
Palo
Verde
Chooz
Bugey III
Savannah
River
Gosgen
ILL
Rovno
10% per year
Reactor Power × Target Mass (MegaWatt-ton)
Baseline
10 m
100 m
1km
10km
100km

Primorskaya
Russia
China
South Korea
KamLAND

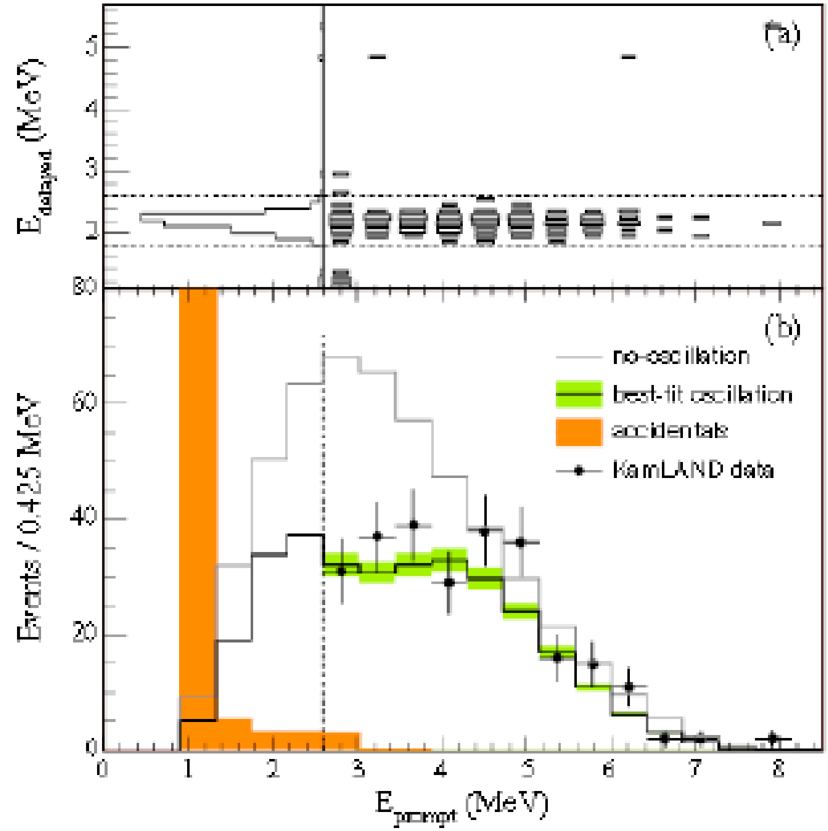
The Source for KAMLAND

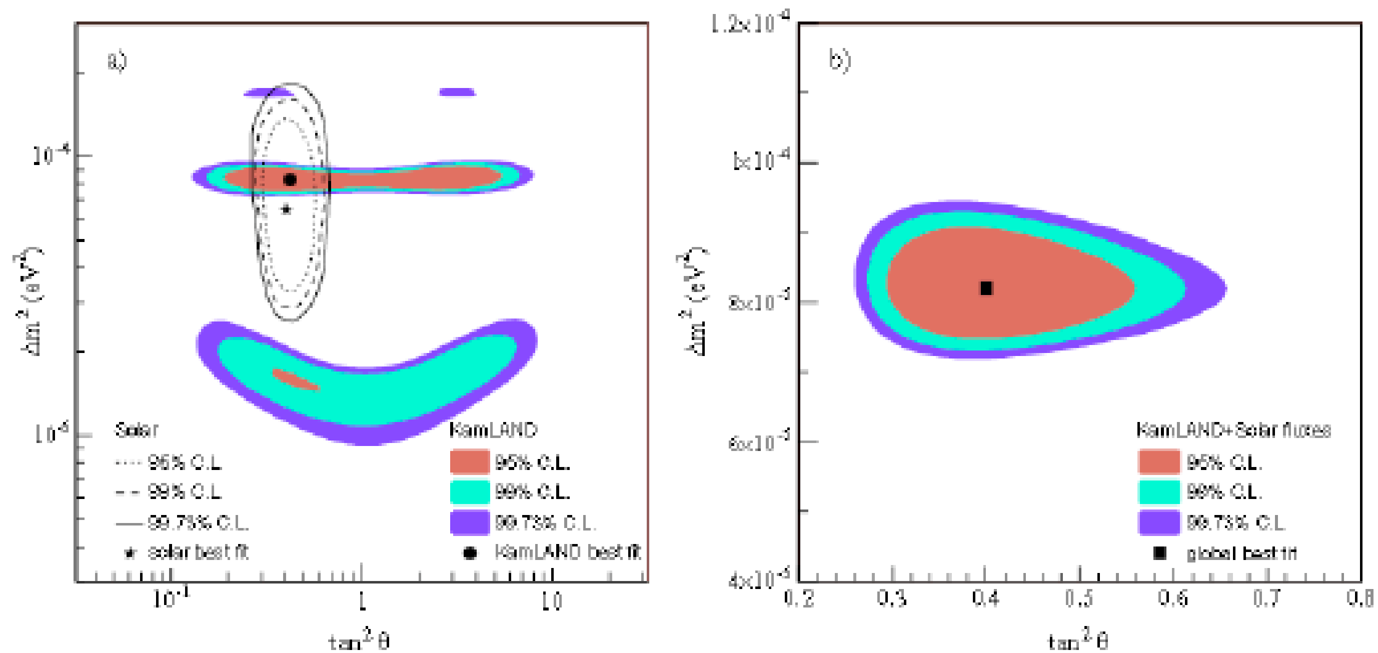


All anti-electron neutrinos

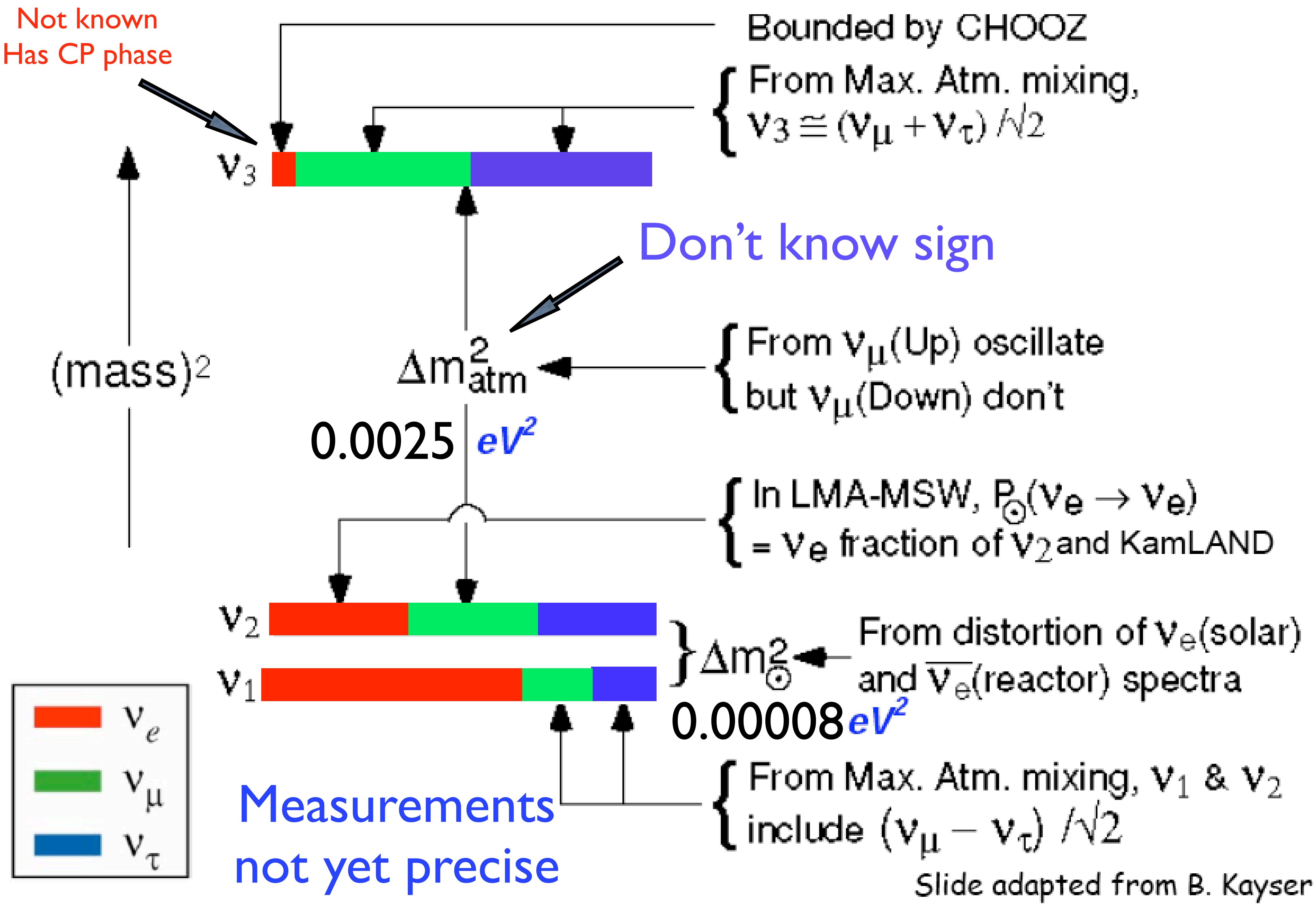
Flux: 4.4e8 /GWT/cm2/sec
@ 1km

rate: 270 /Ton/yr/GWT
@ 1 km Enu>3.4 MeV


(a)
(b)
$E_{delayed}$ (MeV)
Events / 0.425 MeV
no-oscillation
best-fit oscillation
accidentals
KamLAND data
E_{prompt} (MeV)


a)
b)
Δm^2 (eV^2)
$\tan^2\theta$
Solar
95% C.L.
99% C.L.
99.73% C.L.
solar best fit
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
KamLAND best fit
KamLAND+Solar fluxes
95% C.L.
99% C.L.
99.73% C.L.
global best fit

What do we know and how do we know it



3-generation oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{4}$$

xyz convention
all angles:0-90 deg.
(except CP phase)

3-generation formula without matter effect:

$$\begin{aligned} P(\nu_a \to \nu_b) \;=\; & \textstyle\sum_i |U_{ai}|^2 |U_{bi}|^2 \\ & +2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E) \\ & +2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E) \\ & +2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E) \end{aligned}$$

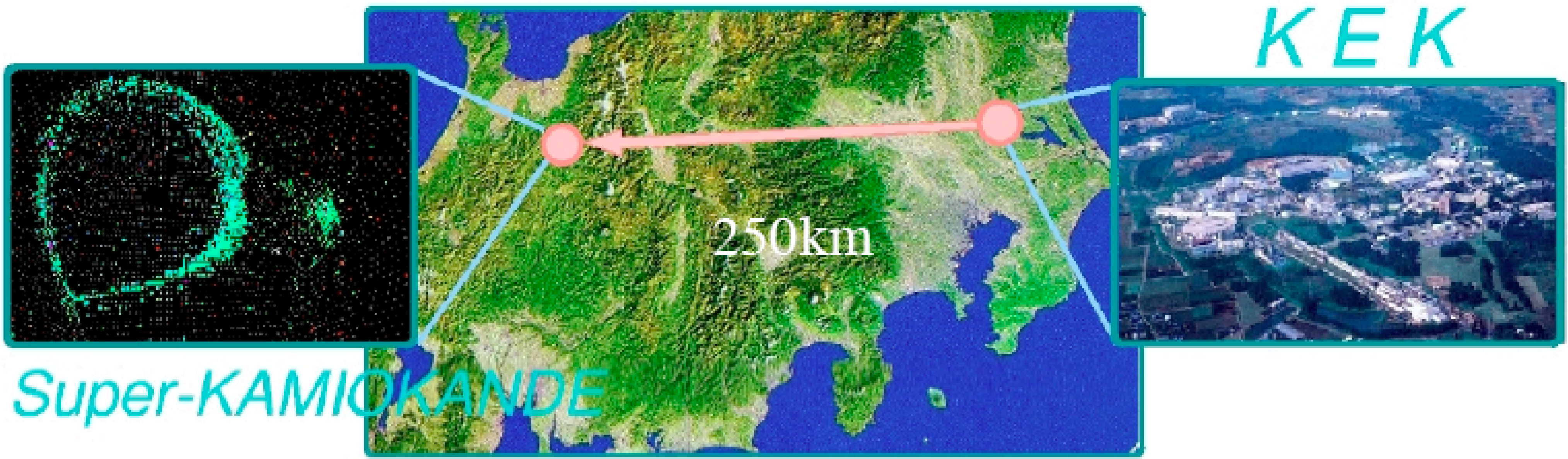
No matter enhancement

For anti-neutrinos take complex conjugate of matrix. Difference from 2 generations: phases.

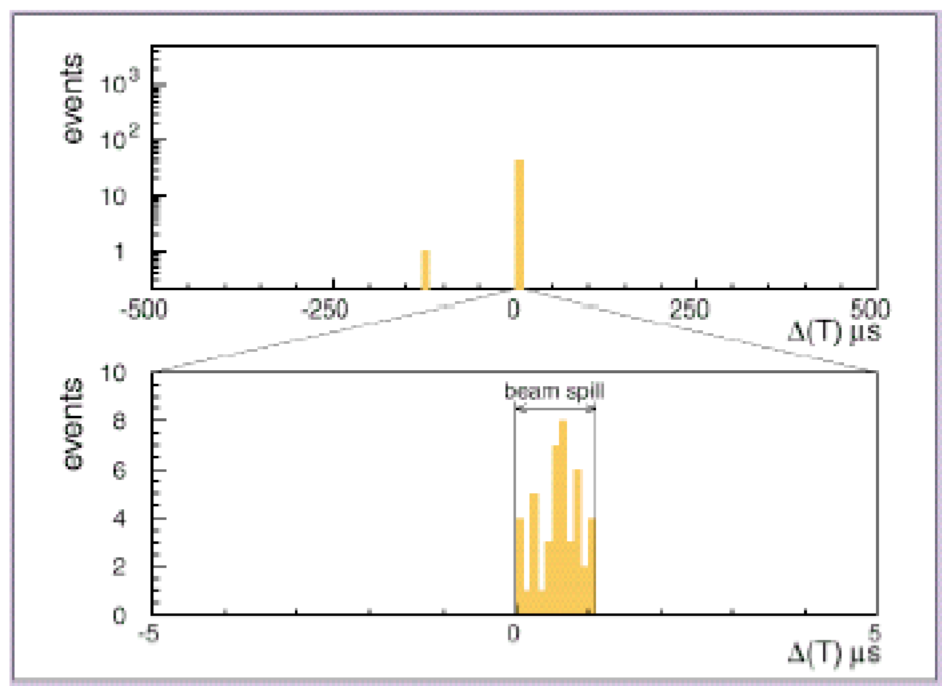
New Age of Accelerator Neutrinos

- For more precise experiments need pure beams of muon type neutrinos (or anti-neutrinos)
- Better controlled characteristics: energy, spectrum, backgrounds, pulsed.
- High energy (>1 GeV) to provide events with long muons. Better resolution.
- Generally called Long Baseline Experiments.

Long Baseline Experiments



First LBL exp. with positive result

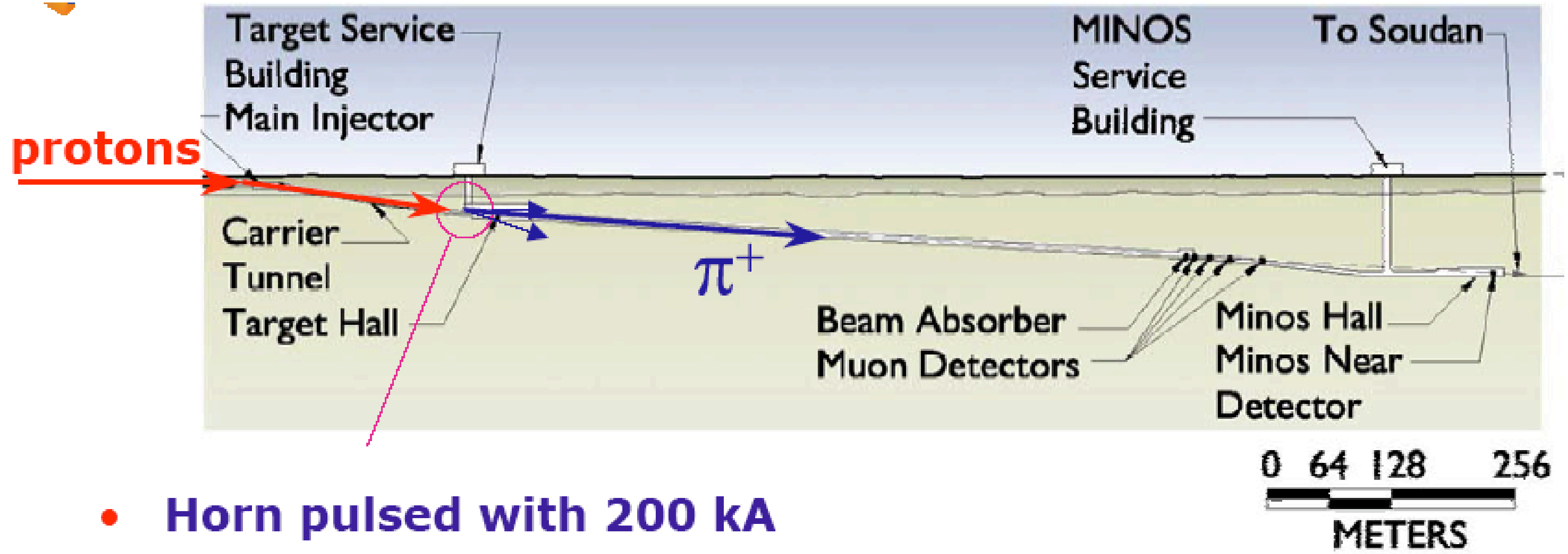


81±8 events no oscillation
56 events observed

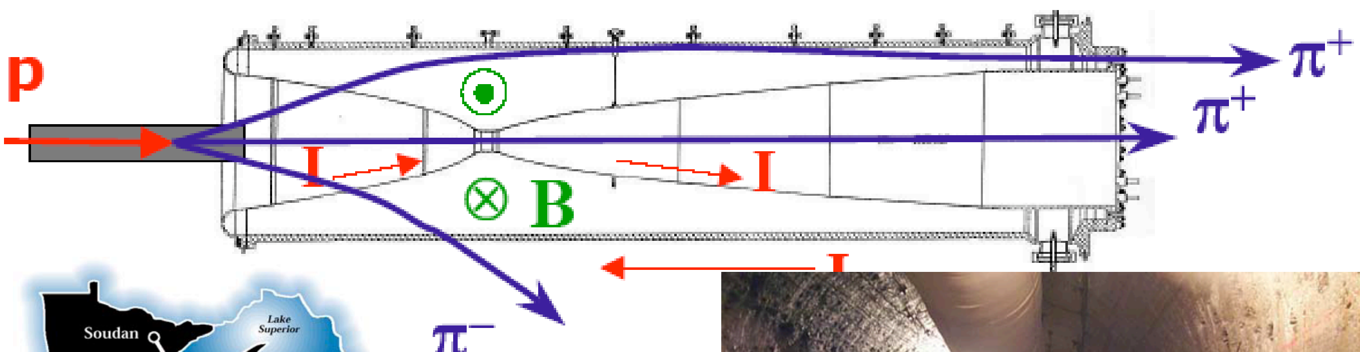
(Fermilab) Main Injector Neutrino Oscillation (MINOS) about to start running.

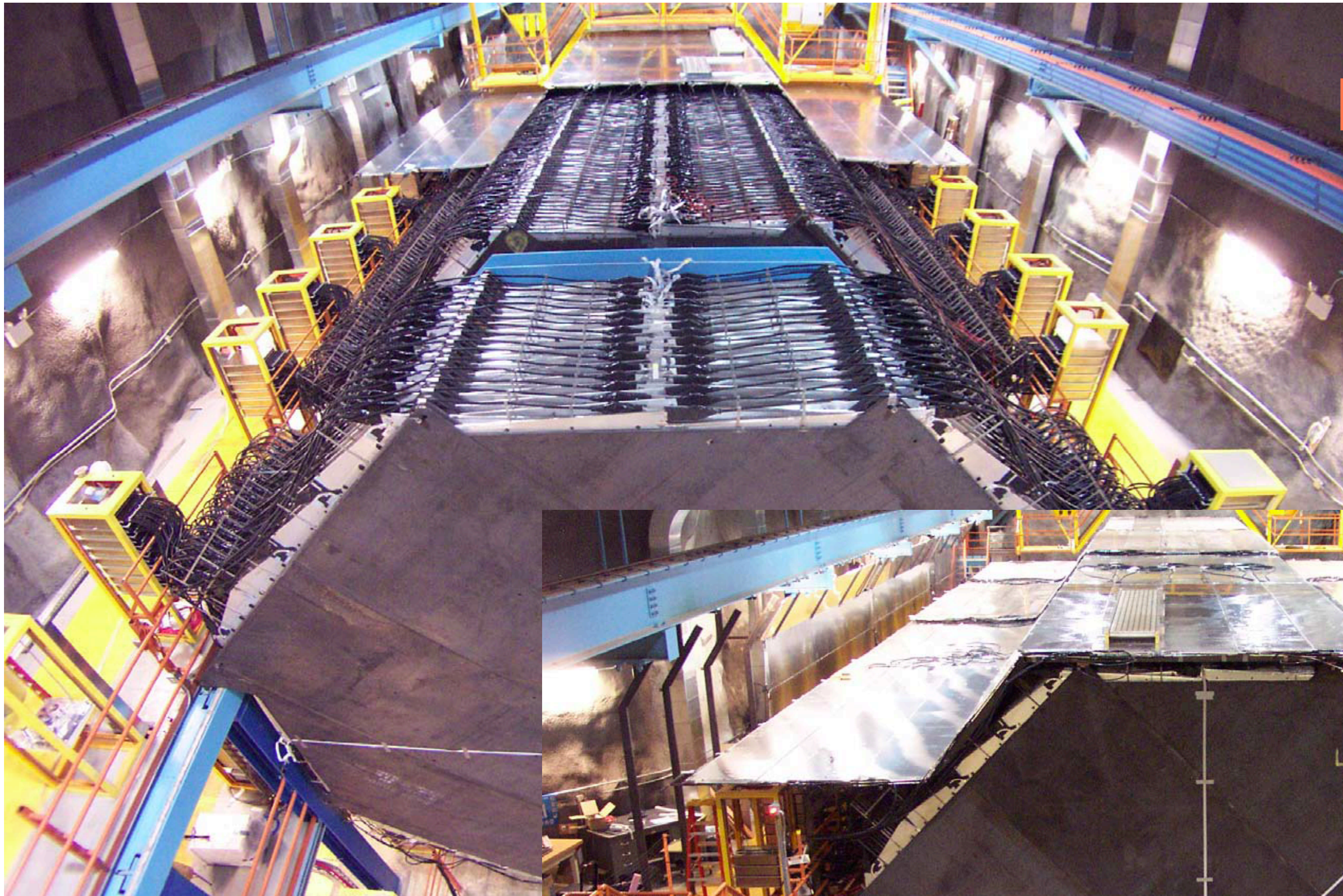
- 120 GeV protons extracted from the MAIN INJECTOR in a single turn (8.7μs)
- 1.9 s cycle time
- *i.e.* ν beam `on' for 8.7μs every 1.9 s
- 2.5x10^{13} protons/pulse
- 0.3 MW on target !
- Initial intensity

  2.5x10^{20} protons/year

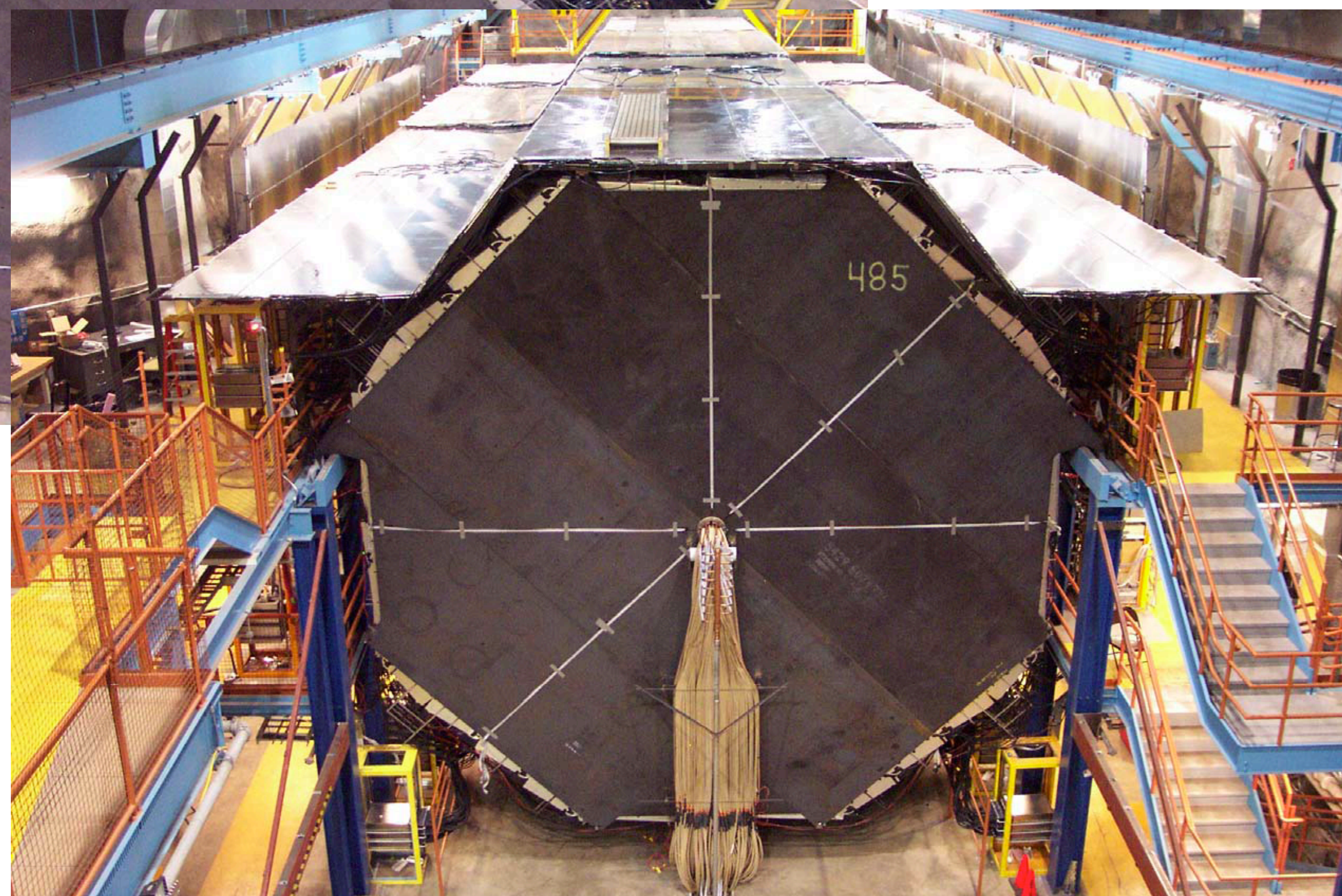


- Horn pulsed with 200 kA
- Toroidal Magnetic field $B \sim I/r$ between inner and outer conducters



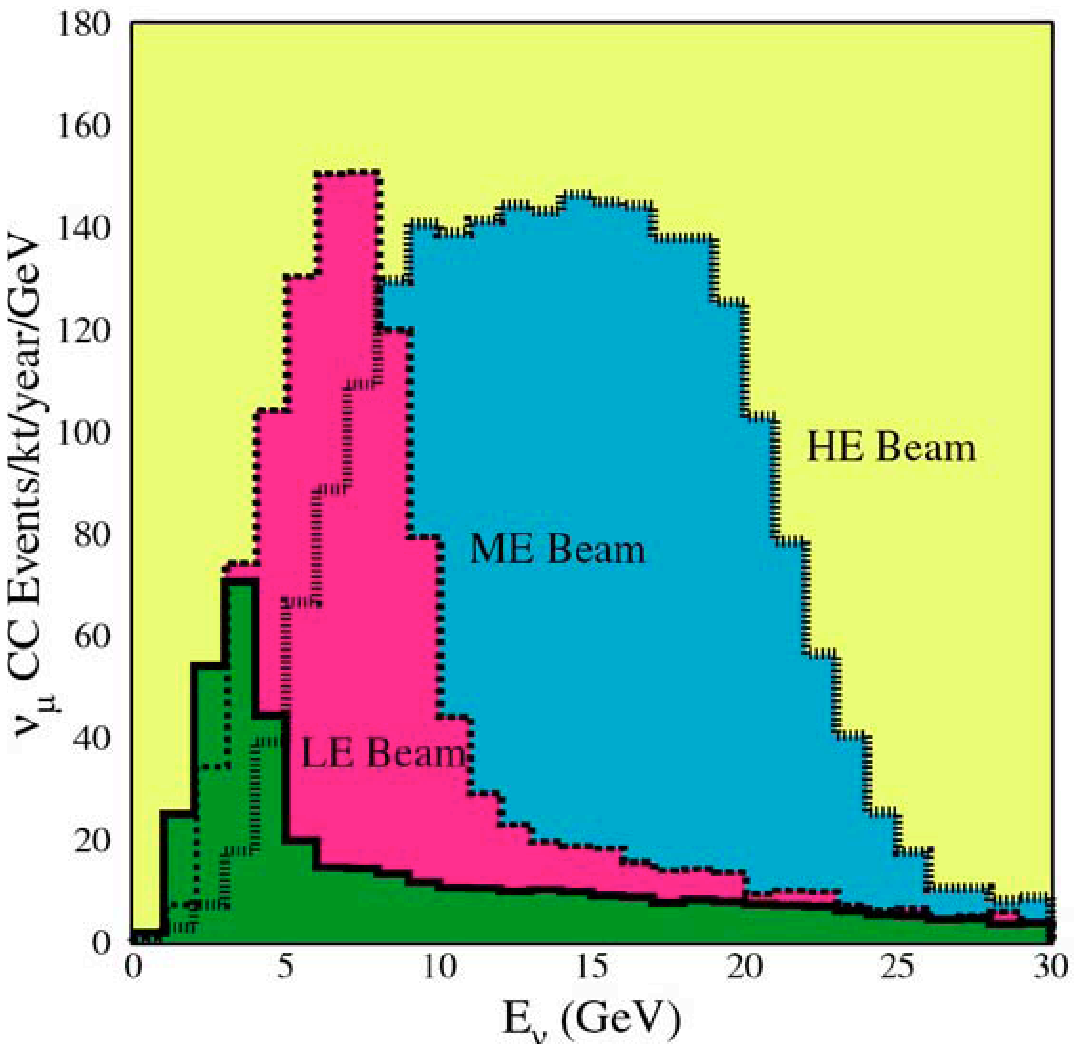


Fully operational in Soudan mine at 2341 ft 730 km from FNAL



Minos detector: Iron/ scintillator 5kT

MINOS Physics Plots



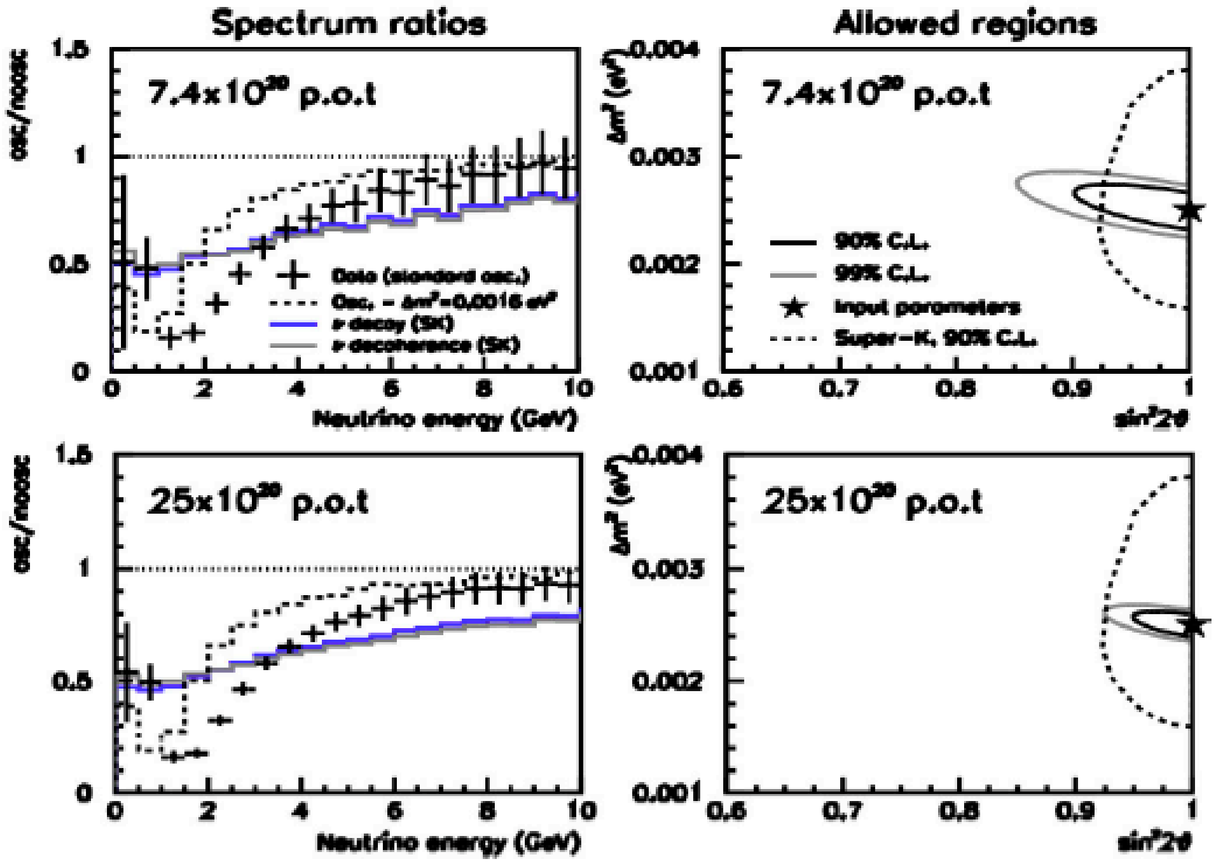
LE BEAM:

ν_μ **CC Events/year:**

Low	Medium	High
1600	4300	9250

(2.5x10^{20} protons on target/year)

★ Measurement of Δm^2 and $\sin^2 2\theta$



For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

Large improvement in precision !

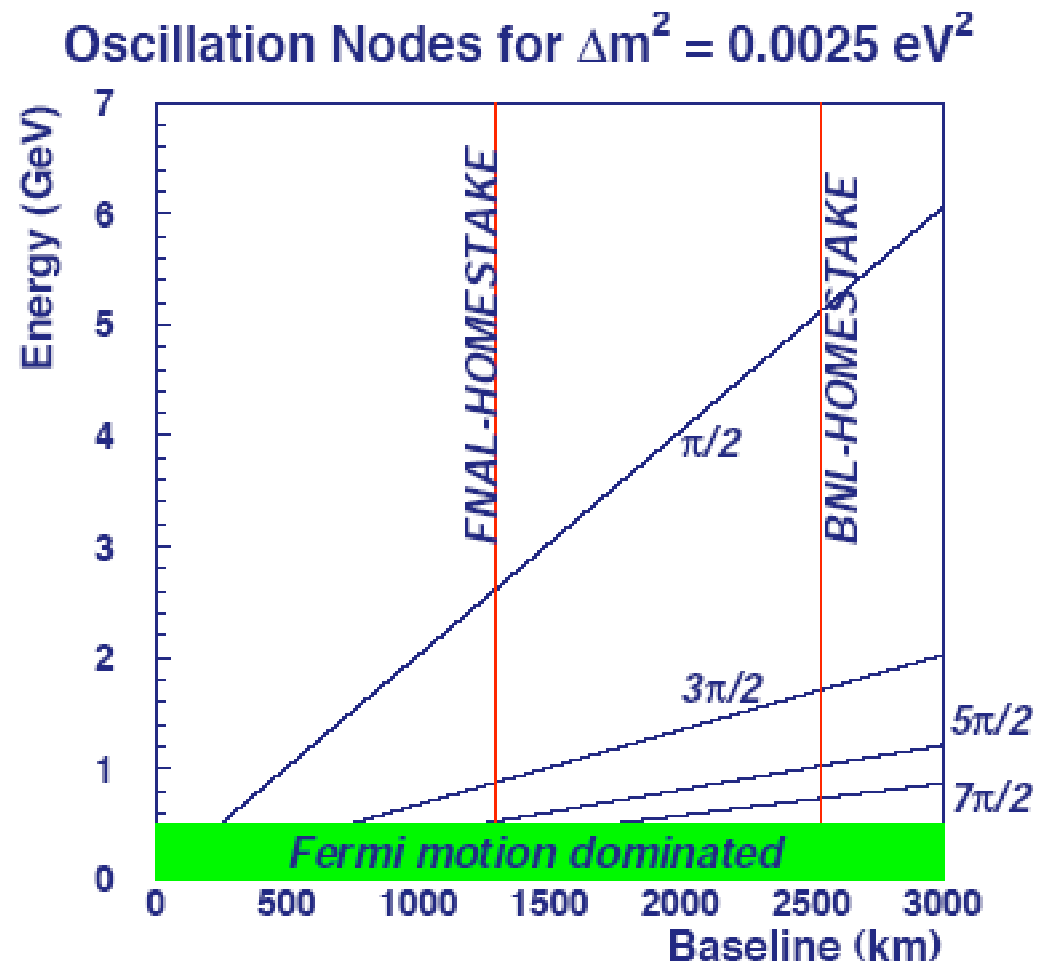
Final sensitivity depends on protons on target

★ Direct measurement of L/E dependence of ν_μ flux

★ Powerful test of flavour oscillations vs. alternative models

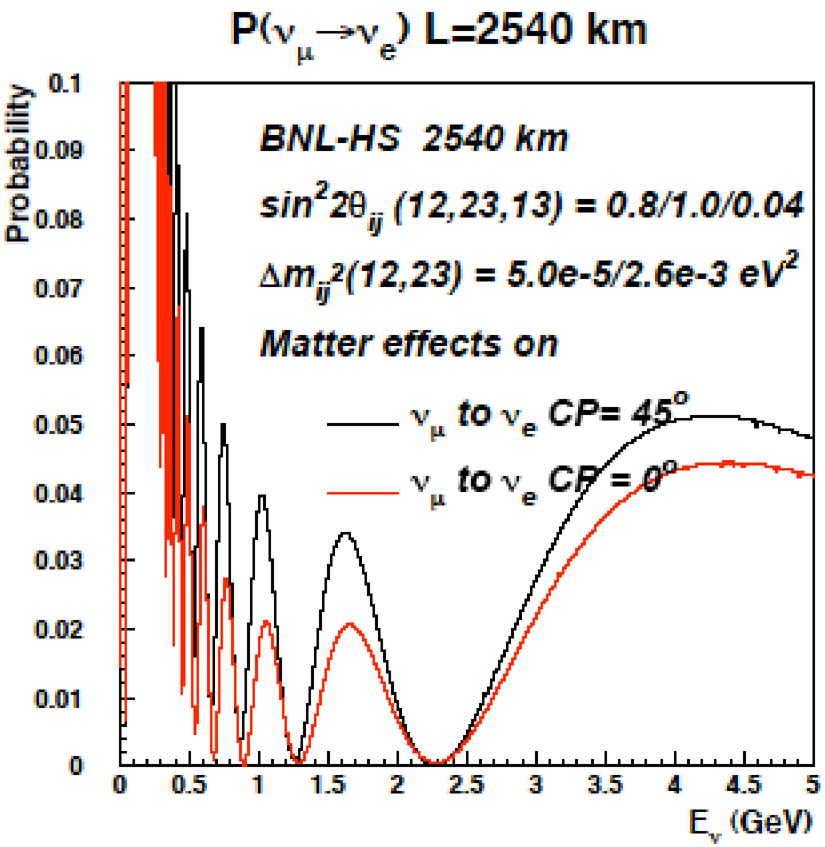
Ultimate Ambitions !

- Must see multiple nodes in muon and electron spectrum for precise measurements
- Need E: 1-6 GeV
- Need ~2000 km
- Need intense beam.
- Need very large detector.



(M. Diwan, hep-ex/0407047)

3 generations/matter effect and CP effect.



General Features

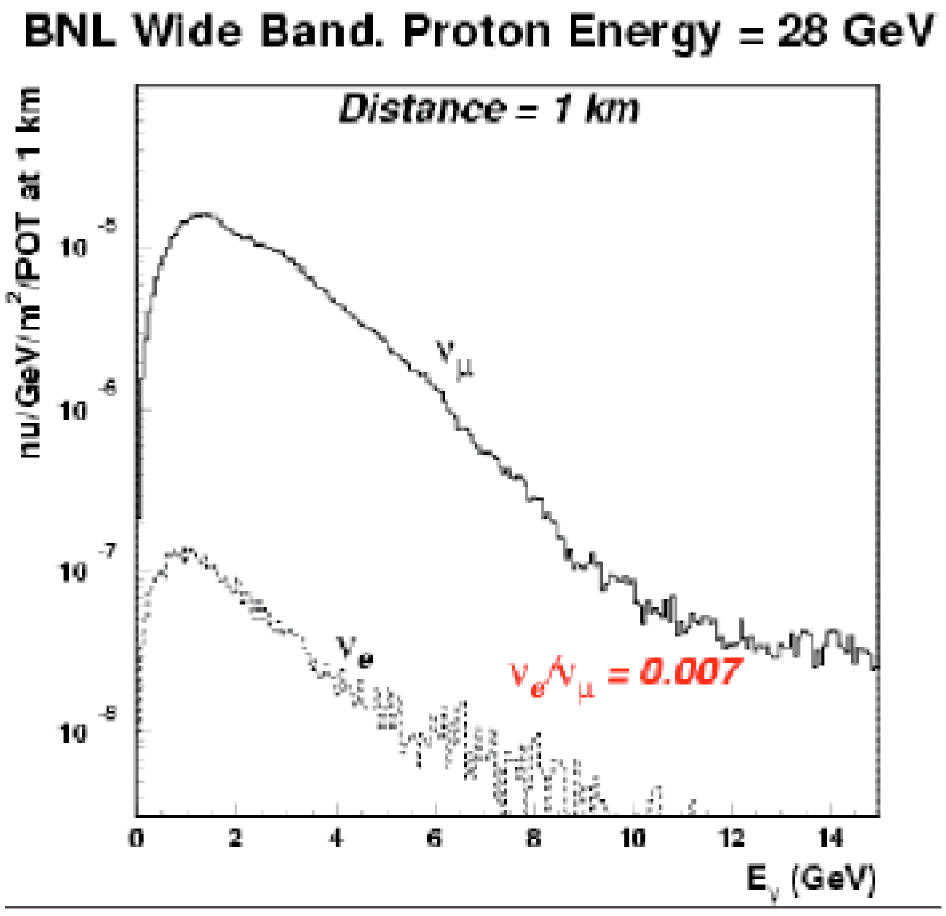
- $0.5-1$ GeV: Δm^2_{12} (LMA) region.
- $1-3$ GeV: CP large effects region
- $>$ 3 GeV: Matter enhanced (ν_μ), suppressed ($\bar{\nu}_\mu$). ($\Delta m^2_{32} > 0$) Region.

- Measure unknown parameter. Theta_13.
- Measure enhancement at >3 GeV to get mass hierarchy.
- Measure spectrum to get CP phase parameter.

BNL → Homestake 1 MW Neutrino Beam

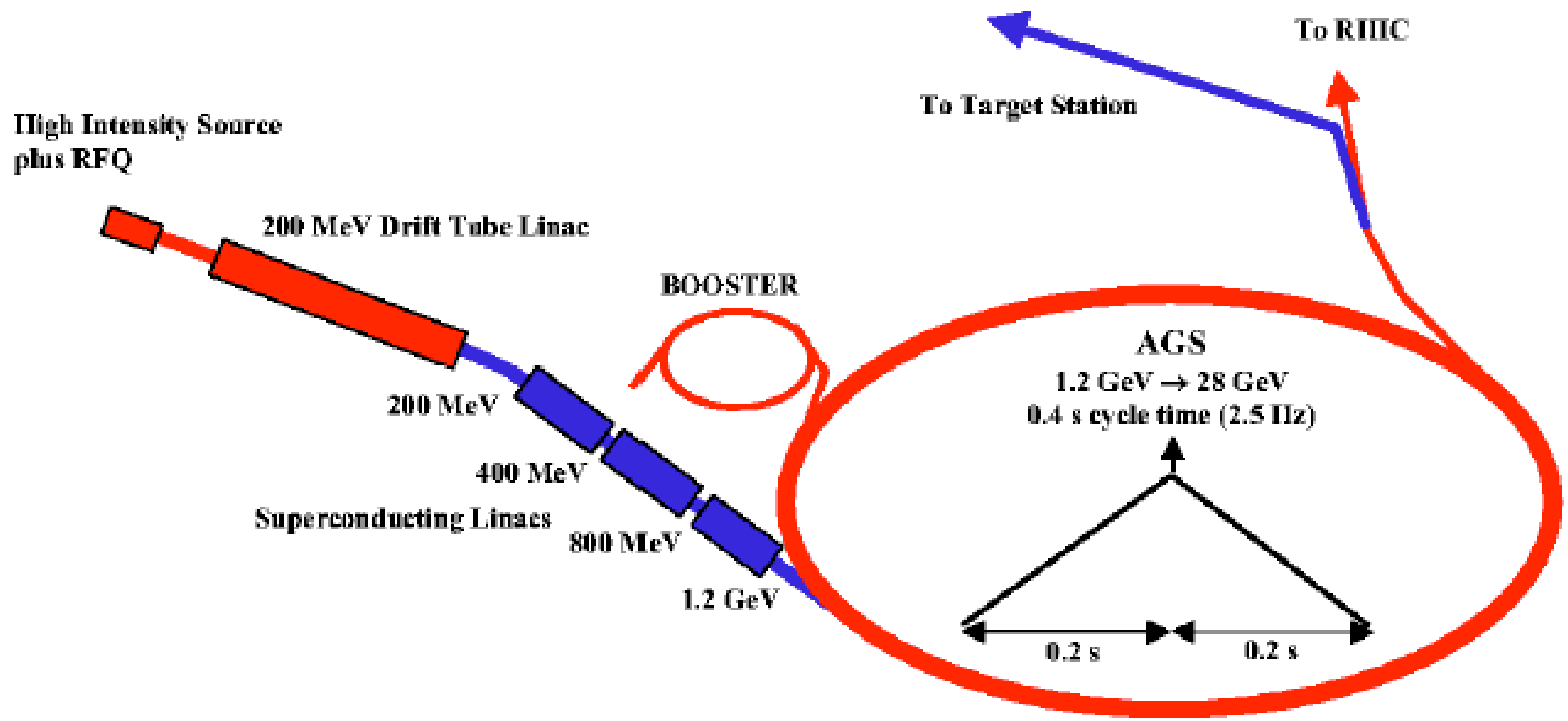
28 GeV protons, 1 MW beam power
500 kT Water Cherenkov detector
5e7 sec of running, Conventional Horn based beam

Neutrino spectrum from AGS



- Proton energy 28 GeV
- 1 MW total power
- ~10 ^{14} proton per pulse
- Cycle 2.5 Hz
- Pulse width 2.5 mu-s
- Horn focused beam with graphite target
- 5x10^{-5} ν/m^2/POT @ 1km
- 52000 CC events.
- 17000 NC events.

BNL-AGS Target Power Upgrade to 1 MW

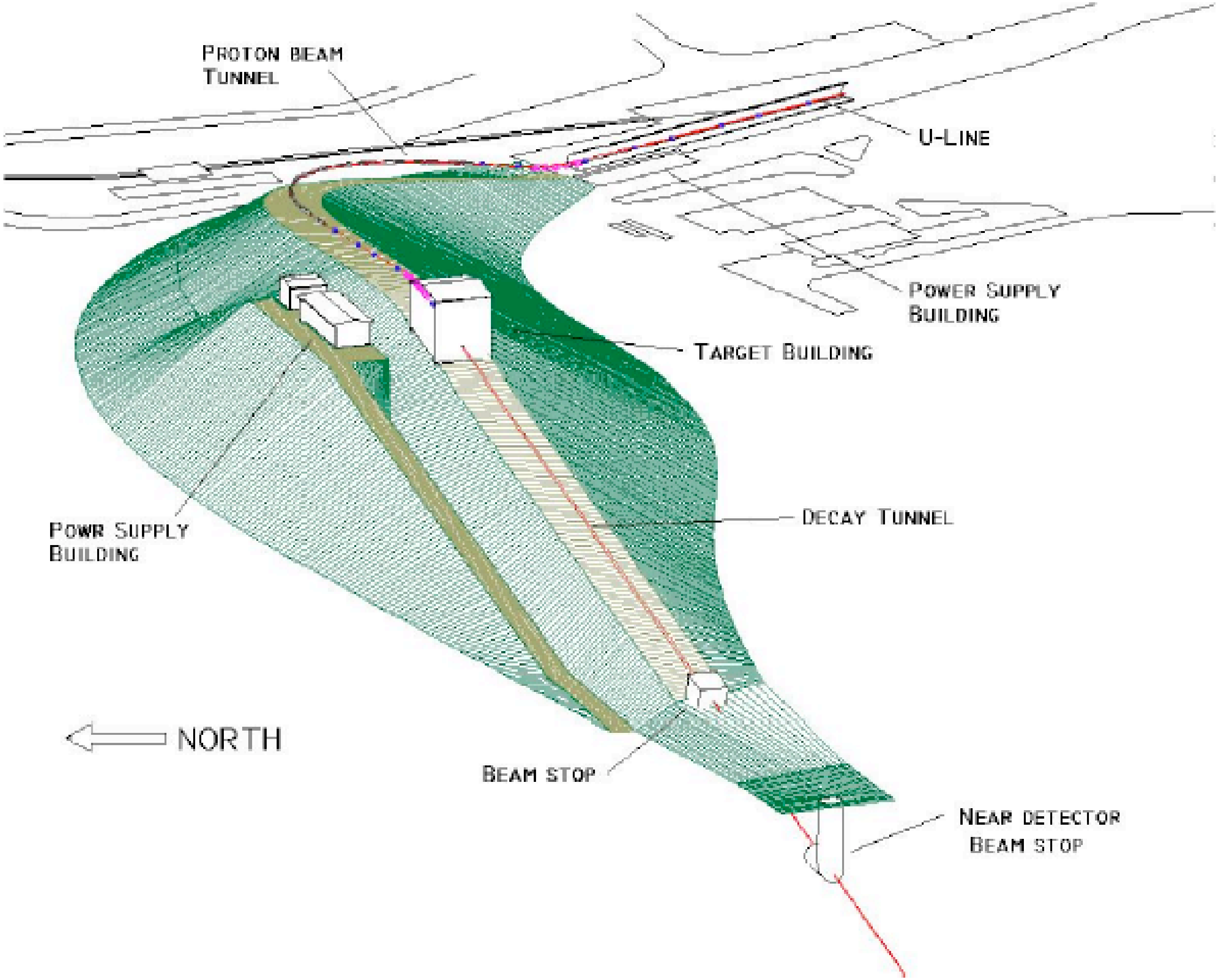


AGS is currently the highest intensity machine.
Simple plan. Run the AGS faster. 2.5 Hz
Need new LINAC @ 1.2 GeV to provide protons.
Cost $265M FY03 (TEC) dollars.
Energy is 28 GeV. 2.5 Hz operation is 1 MW

$$7 \times 10^{13} protons/2sec$$

$$9 \times 10^{13} protons/0.4sec$$

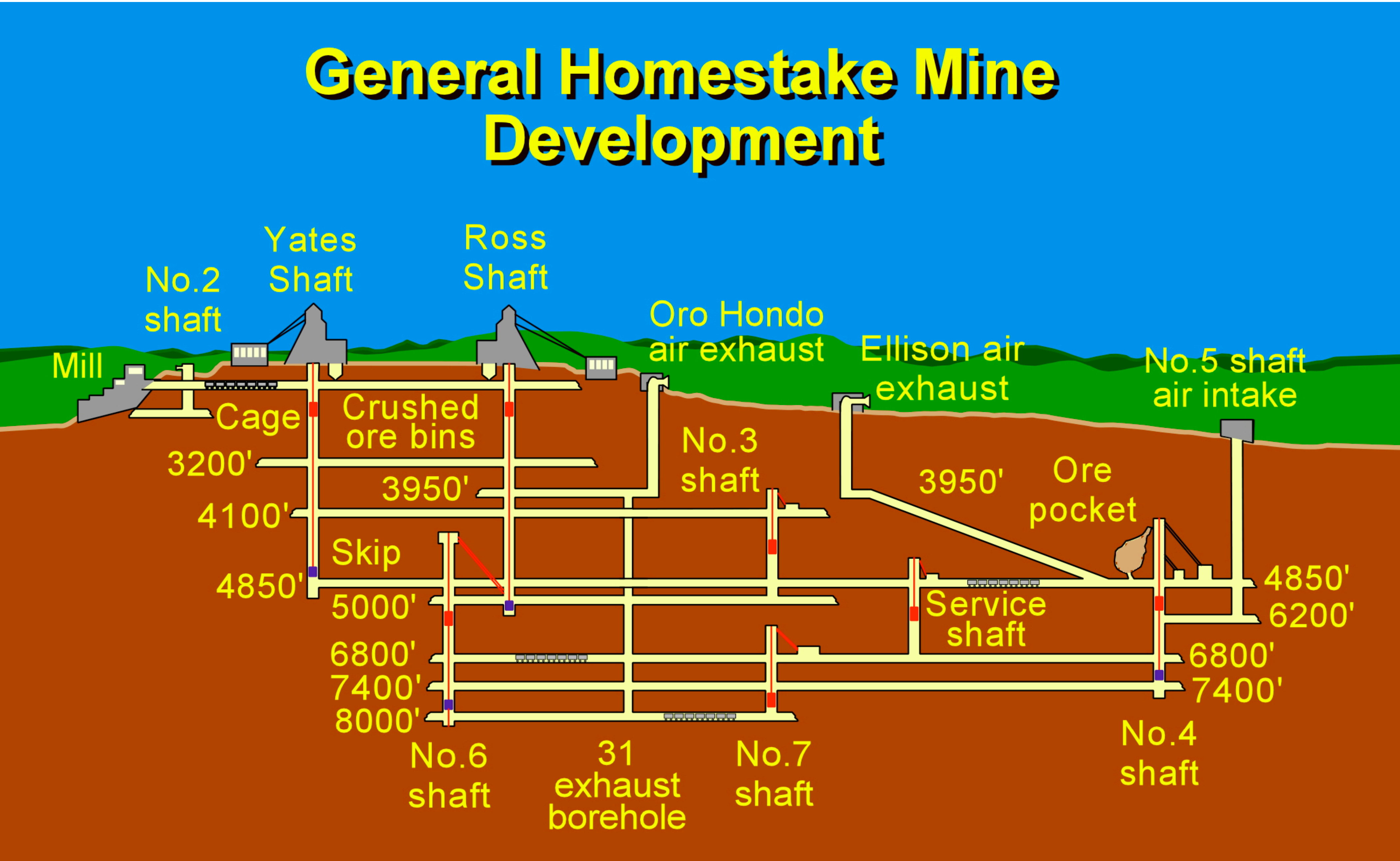
3-D Neutrino Super Beam Perspective



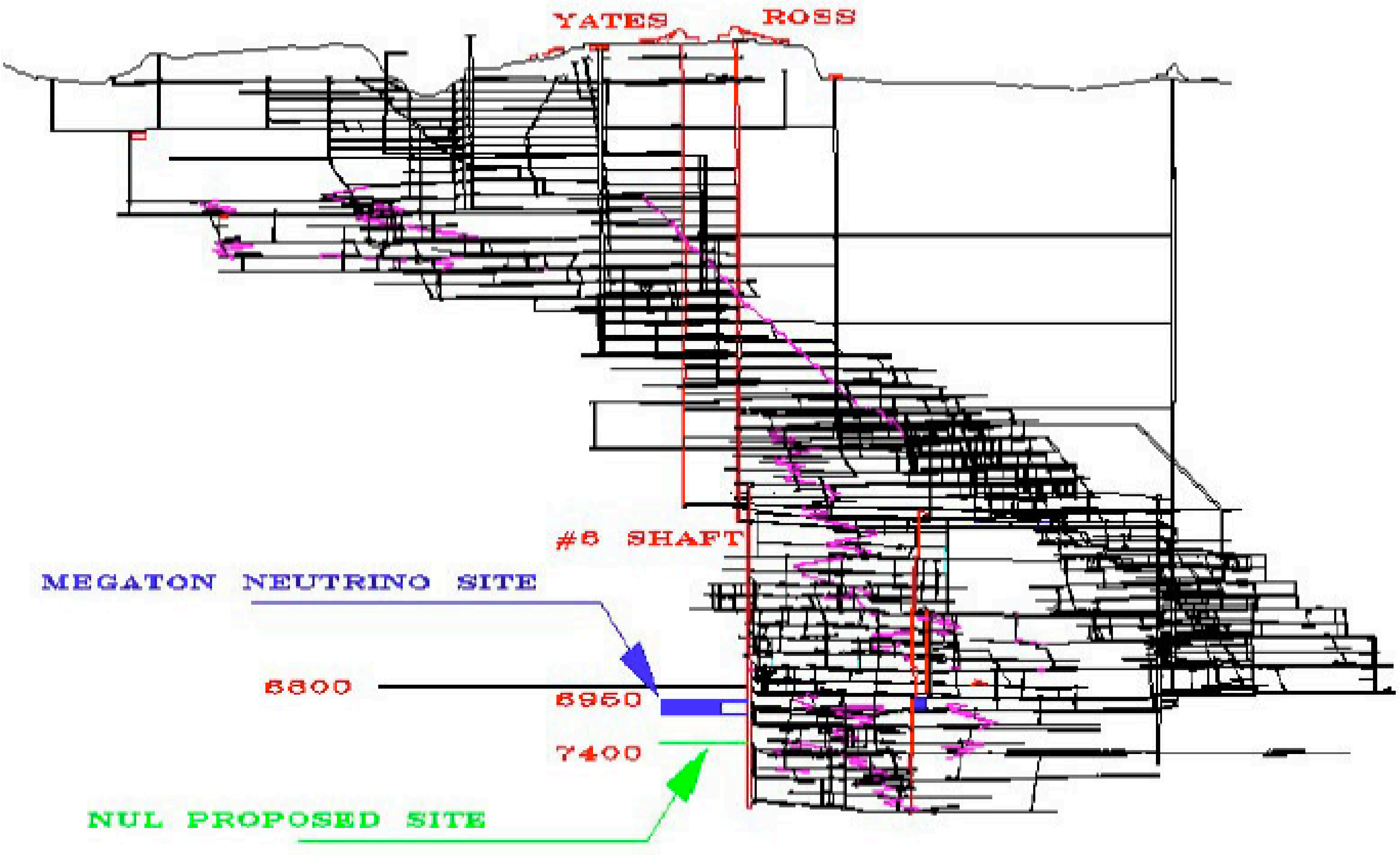
Deep Underground Laboratory Initiative

- New discussion started when Homestake gold mine (site of Davis Clorine experiment) closed.
- National Science Foundation has initiated a series of solicitations.
- S1 - focusses on science first. Identify all science (physics, geology, biology) and infrastructure needs. http://neutrino.lbl.gov/DUSELS-1
- S2 - decide on a suitable site.

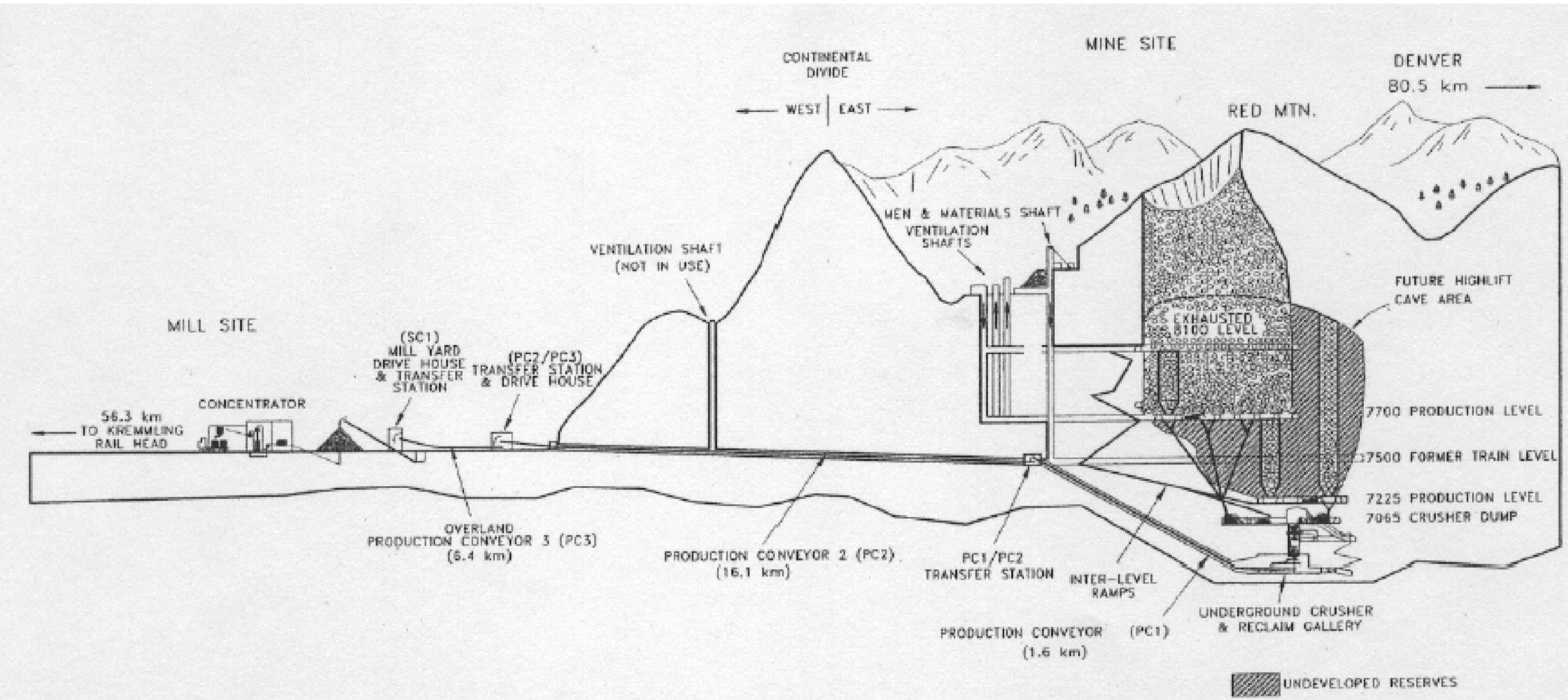
One candidate for DUSEL



True scale is of mine is very large

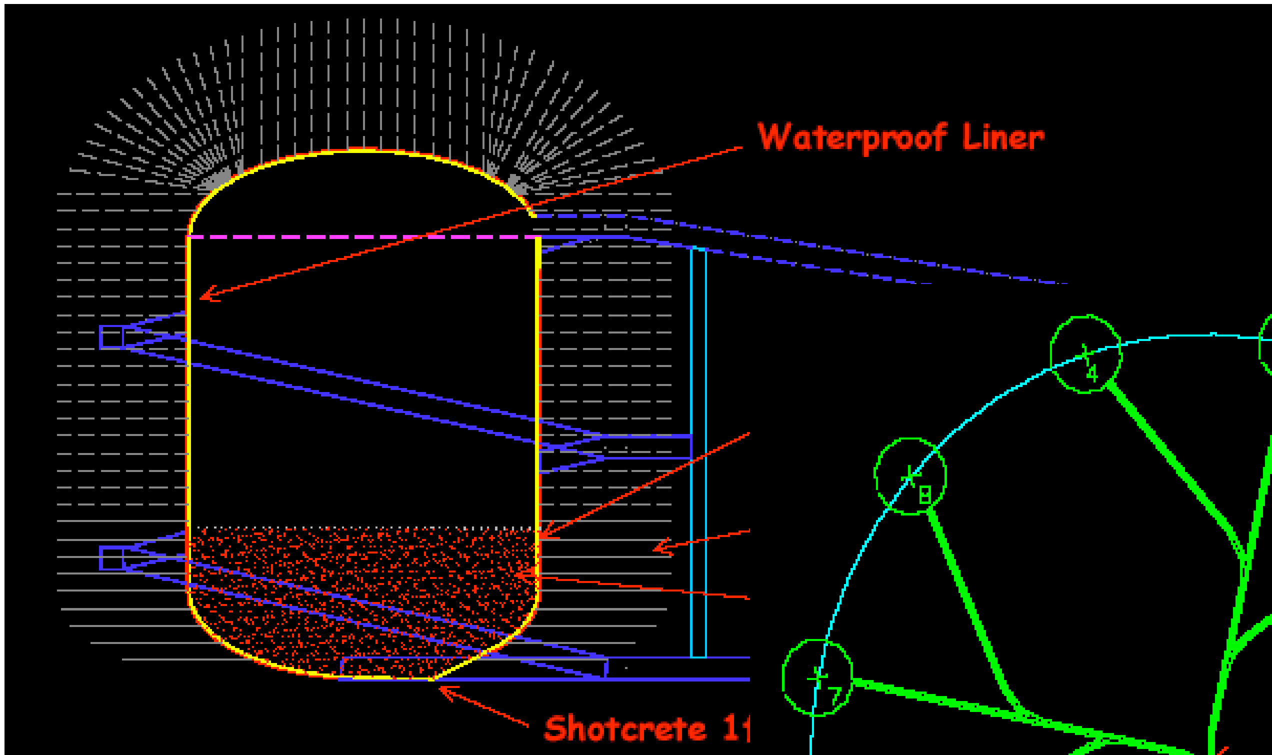

YATES
ROSS
#6 SHAFT
MEGATON NEUTRINO SITE
6800
6950
7400
NUL PROPOSED SITE

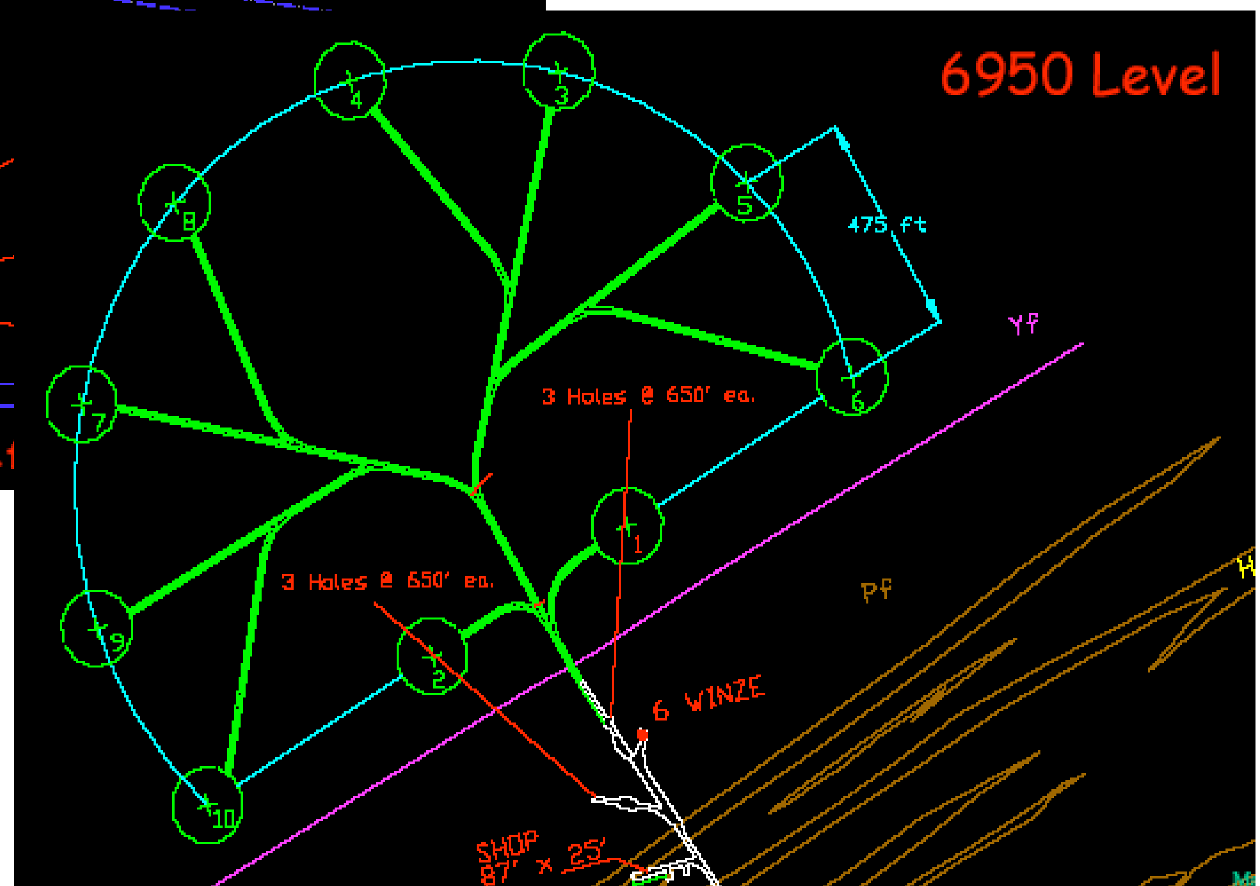
Henderson mine



Homestake 500 kT

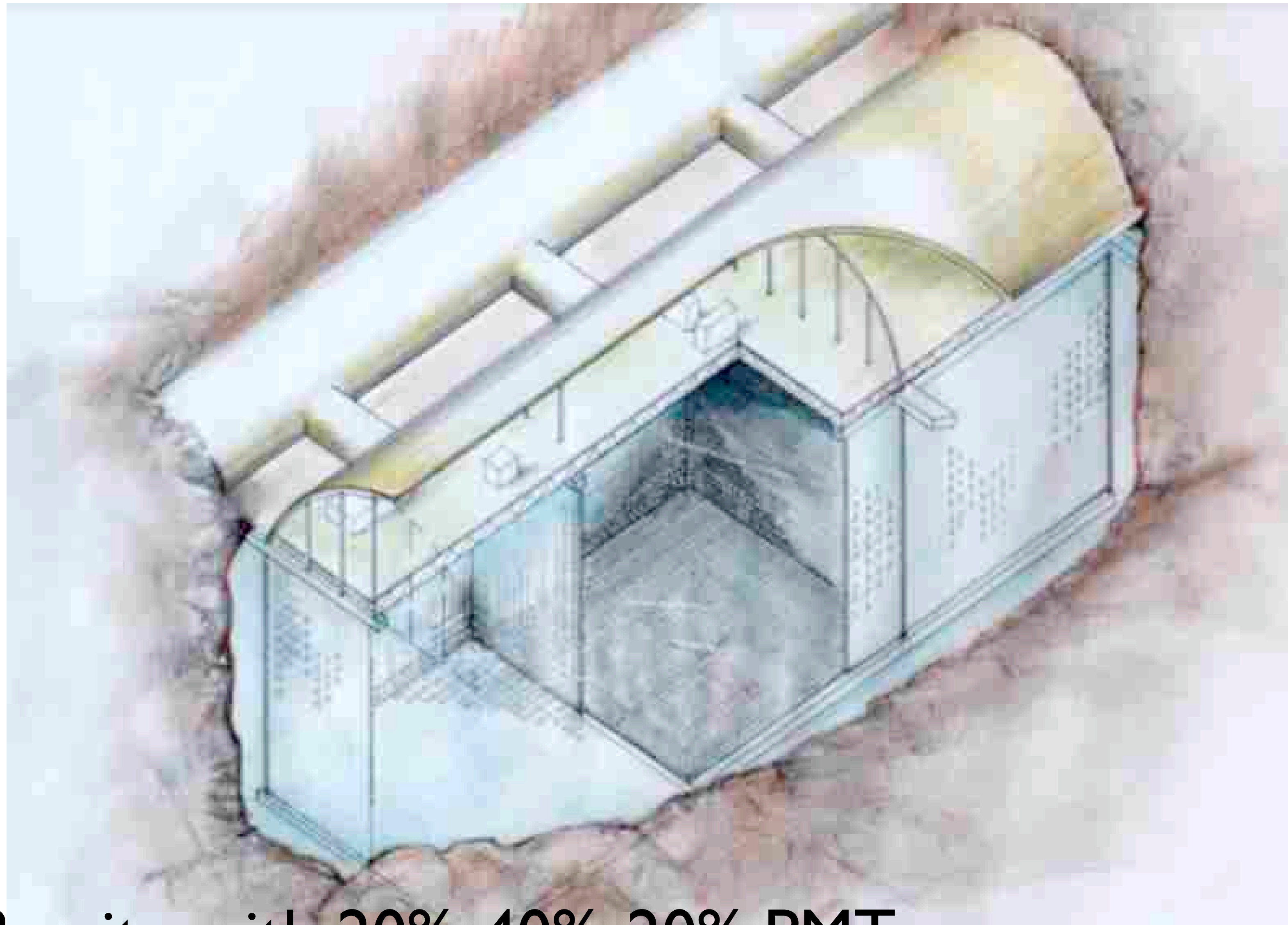
Each tank 100 kT
50 m hi X 50 m dia





Build 10 tanks
in 10 years

UNO schematic



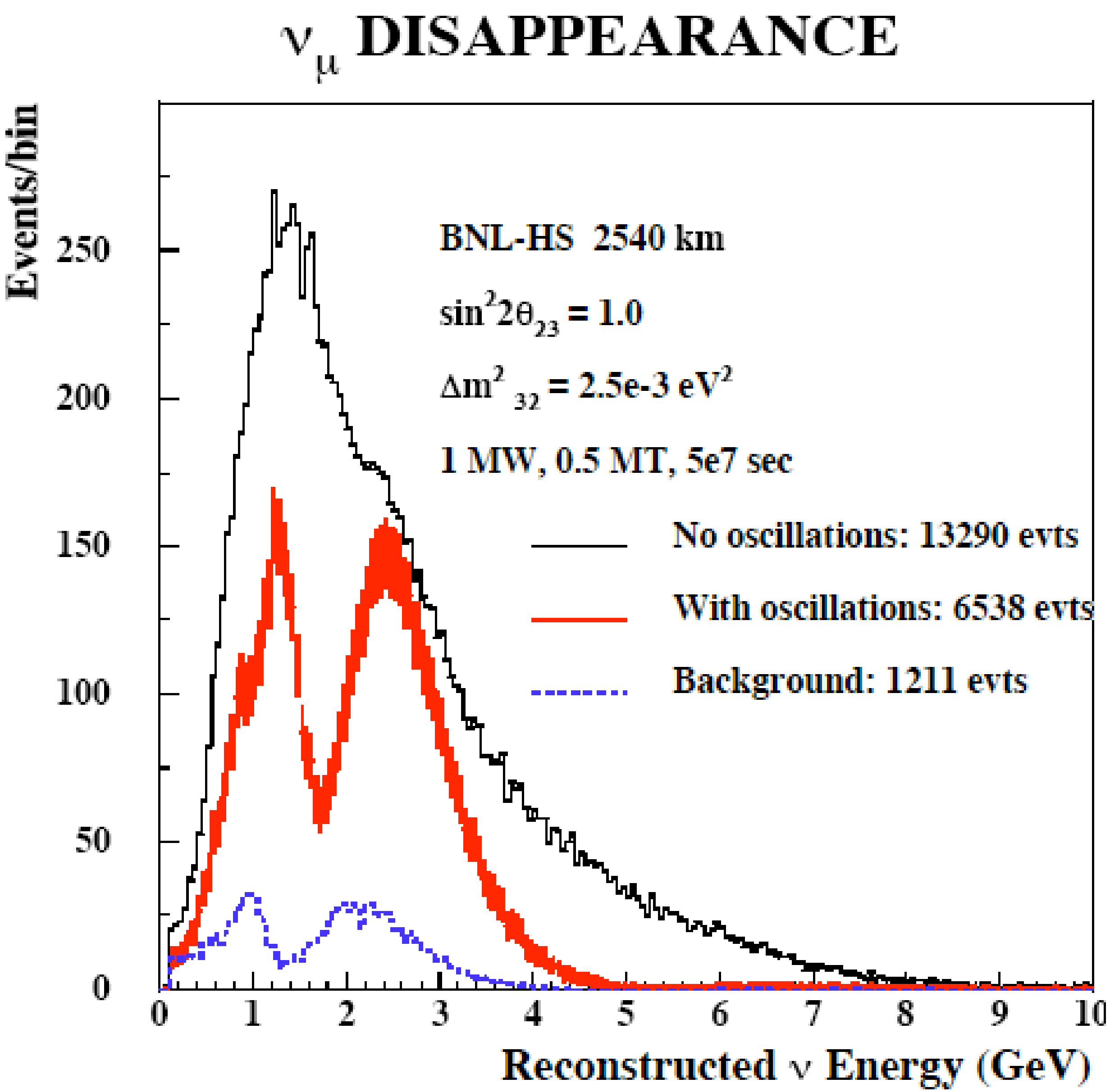
3 units: with 20%, 40%, 20% PMT coverage.
60mX60mX180m

Detector

- Requirements: Very ambitious !
  - 500 kTons fiducial mass for both Proton decay and neutrino astro-physics and neutrino beam physics.
  - ~10 % energy resolution on quasielastic events
  - Muon/electron discrimination at <1%
  - 1, 2, 3 track event separation
  - Showering NC event rejection at factor of ~15
  - Low threshold (~10-15 MeV) for supernova search
  - Part of the detector could have lower threshold for solar neutrino detection.
  - Time resolution of ~few ns for pattern recognition and background reduction.

Recent simulation work looks very good for a water Cherenkov detector

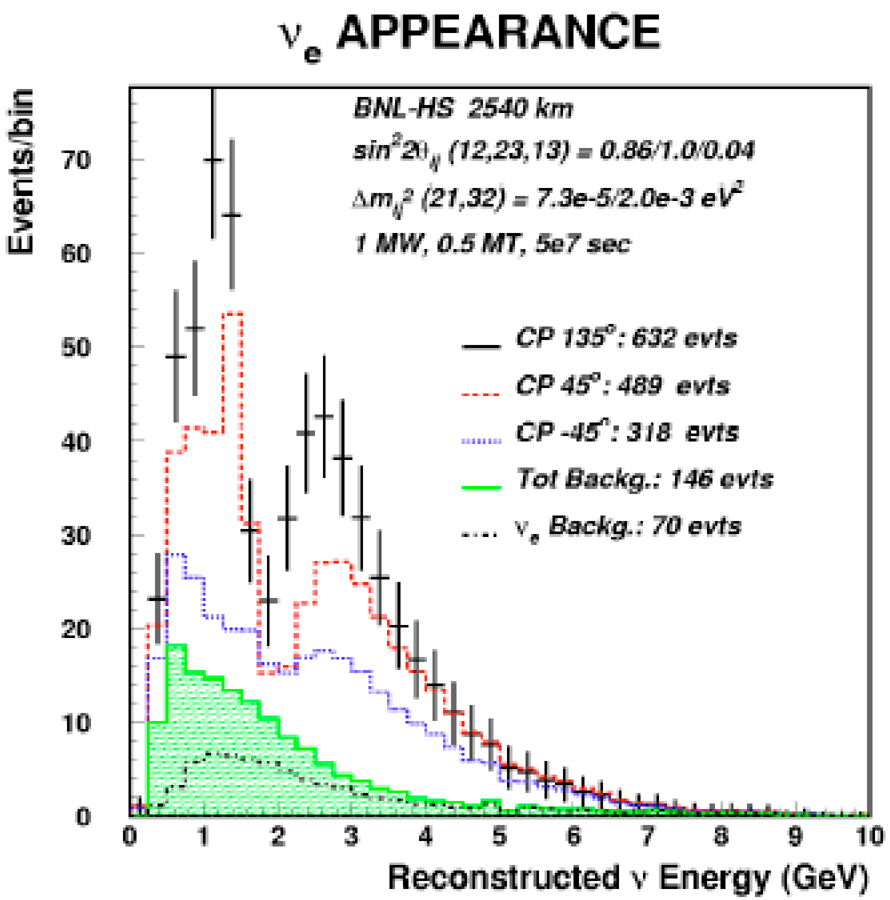
Advantages of a Very Long Baseline

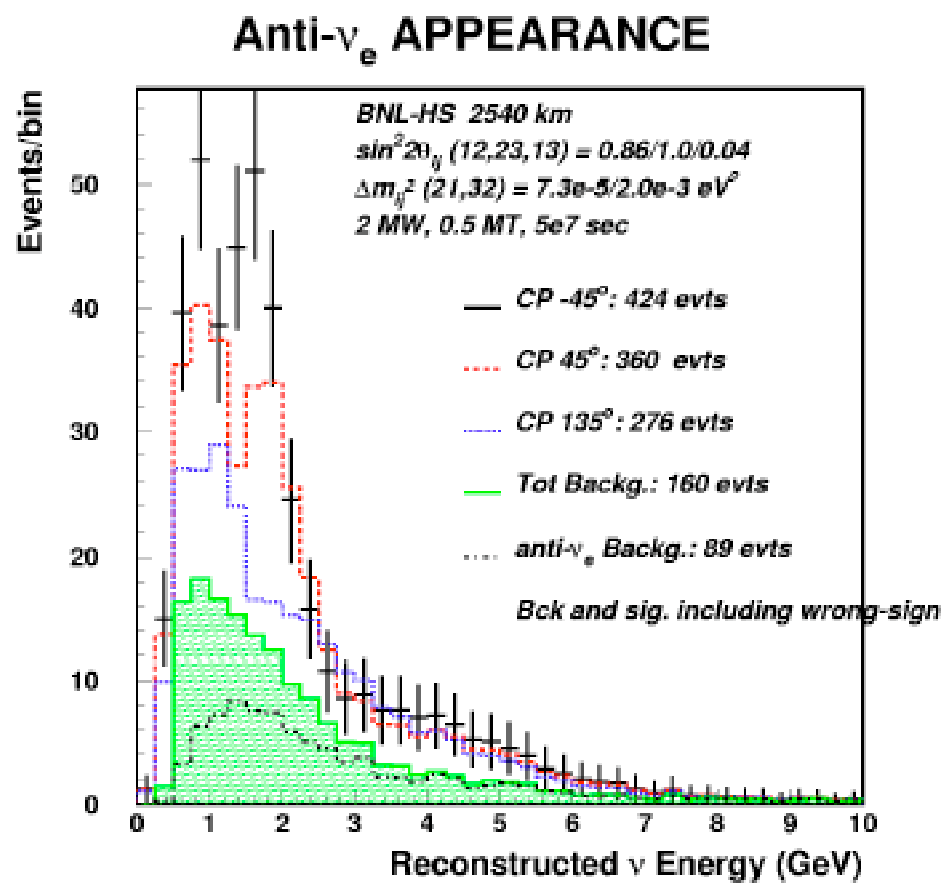


- neutrino oscillations result from the factor $\sin^2(\Delta m_{32}^2\ L\ /\ 4E)$ modulating the ν flux for each flavor (here ν_μ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a *very long baseline* actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the Δm_{32}^2 to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

Neutrino vs. Anti-neutrino

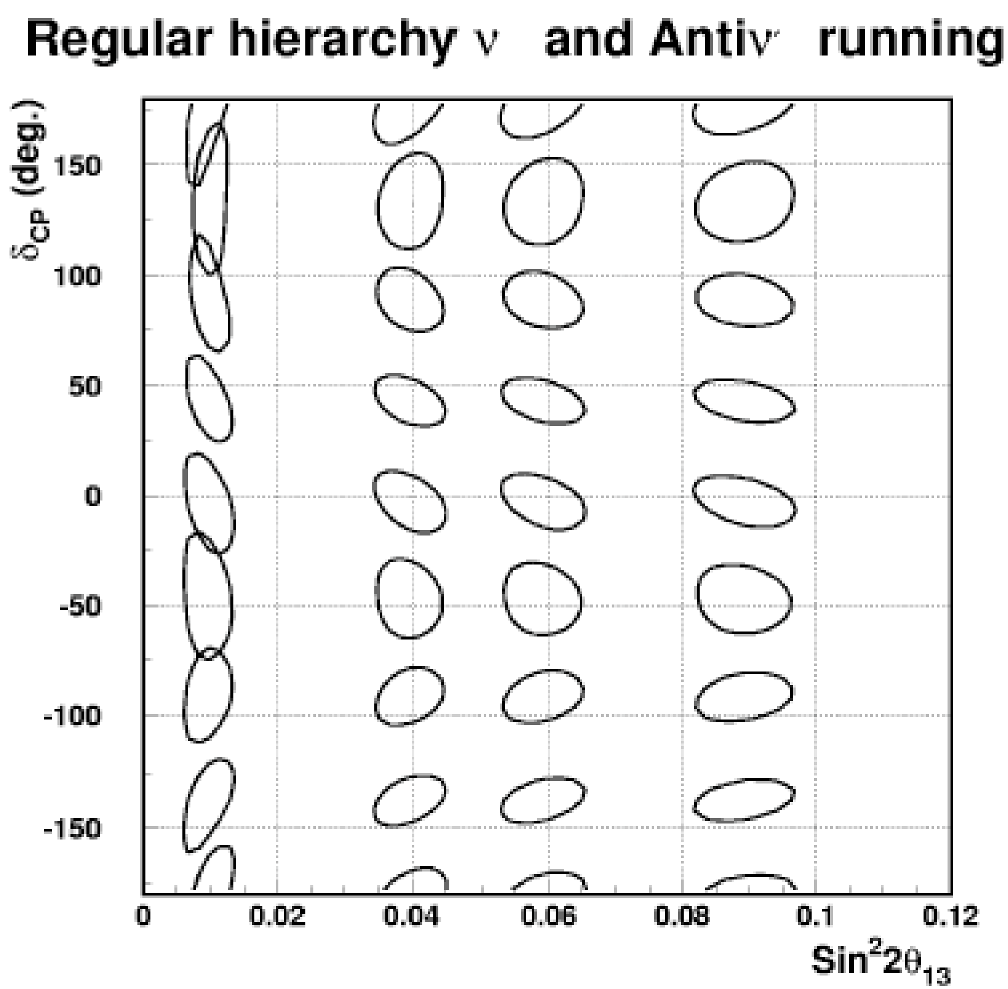
Regular mass ordering





- High energy. Need 2 MW for anti-nu to get same stats
- Spectra get exchanged for reversed mass ordering !

Important Considerations



If signal is well above background CP resolution is indep. of $\sin^2 2\theta_{13}$

Wide band beam and 2540 km eliminate many parameter correlations.

For 3-generation mixing only neutrino running is needed. Anti-neutrino running gives better precision or New physics.

Conclusions

- Neutrino physics entering new phase.
- We can now ask deep questions:
  - Mass: are neutrinos own anti-particles ?
    Do neutrinos violate CP conservation ?
    Relationship of quarks and neutrinos ?
- New facilities of intense beams and large detectors are needed: APS neutrino study.